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ABSTRACT

This technical specialty course is one of thirty-five courses designed for use by two-year postsecondary institutions in five nuclear technician curriculum areas: (1) radiation protection technician, (2) nuclear instrumentation and control technician, (3) nuclear materials processing technician, (4) nuclear quality-assurance/quality-control technician, and (5) nuclear reactor (plant) operator trainee. This course, Control Systems II, contains seven modules: Introduction to Transfer Functions, Frequency Response Analysis, Combination Control Systems, Controller Tuning, Operational Amplifiers, Microprocessor Utilization, and Microprocessor Programming. Each module follows a typical format including the following sections: introduction, module prerequisites, objectives, subject matter, exercises, materials, procedures, data tables, reference materials, and tests. (A master index and suggested program planning guides are also available--see CE 026 856 and CE 026 639-643.) (LRA)

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ED192152

Nuclear Technology Series

COURSE 34

CONTROL SYSTEMS II

CENTER FOR OCCUPATIONAL RESEARCH
AND DEVELOPMENT

4800 LAKEWOOD DRIVE
WACO, TEXAS
76710

CE 026 784

U.S. DEPARTMENT OF HEALTH,
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PREFACE

ABOUT NUCLEAR TECHNOLOGY MODULES

The modules – developed for use in two-year postsecondary technical institutions to prepare technicians for employment – are useful in industry for updating employees in company-sponsored training, and as laboratory texts in engineering schools. The principles, techniques and skills taught in the modules, based on tasks that nuclear technicians perform, were obtained from a nationwide advisory committee of employers of nuclear technicians. Each module was written by a working technical expert/experienced writer team and tested with students.

A module contains the following elements:

Introduction, which identifies the topic and often includes a rationale for studying the material.

Module Prerequisites, which identify the material a student should be familiar with before studying the module.

Objectives, which clearly identify what the student is expected to know for satisfactory module completion. The objectives, stated in terms of action-oriented behaviors, include such action words as operate, measure, calculate, identify and define, rather than words with many interpretations, such as know, understand, learn and appreciate.

Subject Matter, which presents the background theory and techniques supportive to the objectives of the module. Subject matter is written with the technical student in mind.

Exercises, which provide practical problems to which the student can apply this new knowledge.

Materials, which identify the equipment required to complete the laboratory procedure.

Procedures, which is the experiment section, or "hands-on" portion of the module (including step-by-step instruction) designed to reinforce student learning.

Data Tables, which are included in most modules for the first year (or basic) courses to help the student learn how to collect and organize data.

Reference Materials, which are included as suggestions for supplementary reading/viewing for the student.

Test, which measures the student's achievement of the prestated objectives.

A helpful Index has been added at the end of each course.

The materials contained herein were developed pursuant to a contract with the Office of Education, U.S. Department of Health, Education and Welfare: Contract No. 300780582. Contractors undertaking such projects under Government sponsorship are encouraged to express freely their professional judgment in the conduct of the project. Points of view or opinions stated do not, therefore, necessarily represent official Office of Education position or policy.

The Nuclear Technology Series consists of five curricula:

- Nuclear Reactor (Plant) Operator Trainee.
- Radiation Protection Technician.
- Nuclear Materials Processing Technician.
- Nuclear Quality-Assurance/Quality-Control Technician.
- Nuclear Instrumentation and Control Technician.

The completed Nuclear Technology Series consists of the following 35 technical specialty courses:

- Radiation Physics.
- Radiation Protection I.
- Principles of Process Instrumentation.
- Heat Transfer and Fluid Flow.
- Introduction to Nuclear Systems.
- Instrumentation and Control of Reactors and Plant Systems.
- Reactor Operations.
- Reactor Safety.
- Reactor Auxiliary Systems.
- Power Plant Systems.
- Radiation Detection and Measurement.
- Reactor Physics.
- Power Plant Chemistry.
- Introduction to Quality Assurance/Quality Control.
- Metallurgy and Metals Properties.
- Mechanical Component Characteristics and Specifications.
- Radiation Protection II.
- Radiological Emergencies.
- Radiation Shielding.
- Radiation Monitoring Techniques (Radiochemical).
- Radioactive Materials Disposal and Management.
- Advanced Radionuclide Analysis.
- Nuclear Chemical Processes.
- Nuclear Systems and Safety.
- Radioactive Material Handling Techniques.
- Nondestructive Examination (NDE) Techniques I.
- Metrology.
- Welding Inspection.
- Civil/Structural Inspection.
- Mechanical Inspection.
- Quality-Assurance Practices.
- Nondestructive Examination (NDE) Techniques II.
- Control Systems I.
- Control Systems II.
- Power Plant Electrical Systems and Components.

Availability: Instructional modules are available individually or by courses from:

Center for Occupational Research and Development
4800 Lakewood Drive, Suite 5
Waco, Texas 76710
Telephone (817) 772-8756

Printed:

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MODULE 34-1 Introduction to Transfer Functions
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MODULE 34-3 Combination Control Systems
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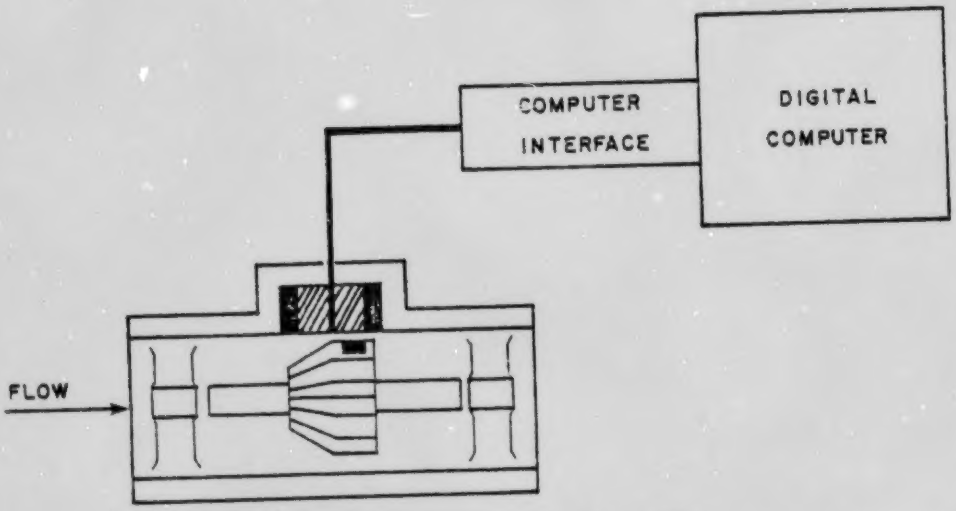
NUCLEAR TECHNOLOGY

MODULE 34 - 1

INTRODUCTION TO TRANSFER FUNCTIONS


COMPUTER INTERFACE
DIGITAL COMPUTER
FLOW

CONTROL SYSTEMS II
COURSE 34

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COURSE MODULES

CONTENTS

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INTRODUCTION

The primary purpose of control system applications is the automatic control of processes. This purpose can be accomplished best when parameters that reveal certain process-dynamic properties are established. The transfer function of a measurement indicates how the output of the measurement system varies with the input variable being measured. This module lists and defines the elements of a system that determine the dynamic characteristics and explains methods for the study of these properties.

MODULE PREREQUISITES

The student should have completed Course 3, "Principles of Process Instrumentation"; Course 6, "Instrumentation and Control of Reactors and Plant Systems"; and Course 33, "Control Systems I."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms, and calculate the quantities represented by each:
    - Transfer function.
    - Resistance (3 types).

    Capacitance (3 types).
    Inertia.
    Inertance.
    Dead time (3 types).

2. Discuss the use of transfer function.
3. Explain the purpose and use of Laplace transforms.
4. Explain frequency domain.
5. Discuss time domain.

TRANSFER FUNCTION

The transfer function of a system is the way in which an input signal is affected in time and magnitude by the system to produce an output signal. The basic elements of a system – resistance, capacitance, inertia, and dead time – are the factors that relate output signal to input signal. Transfer function is a very important consideration in the study of dynamic characteristics, and is necessary in the selection of instrument parameters to the process system. The parameters of the process controller are especially important.

For any control system, the quality of a process depends upon proper selection, application, and control-mode settings of the components in the control loop. These factors are discussed in detail in Module 34-4, "Controller Tuning."

LAPLACE TRANSFORMS

The four basic elements that determine the transfer function of a system act independently of one other to determine input/output relationship. This relationship can be described mathematically by differential equations that contain derivatives of a variable that represent rate of change of the variable. Derivatives represent rate of change in the equations that define the basic elements of a system. The block representative of a typical control system with the differential equation is shown in Figure 34-1-1. The differential equation states that input (m) is equal to output (h), plus π, times rate of change of the output dH/dt.

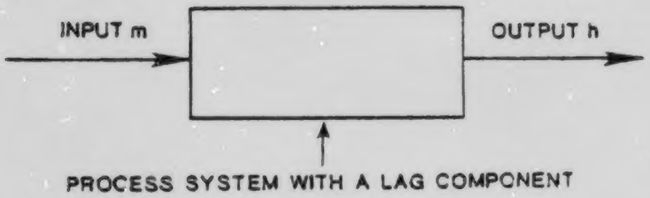


Figure 34-1-1. Block representation of a system with lag components.

Although most control systems are described by differential equations, control-system design includes a transform to avoid use of operational calculus. The Laplace transform changes the differential equation into an algebraic equation. The algebraic equation then is solved by algebraic manipulation. The differential equation of a component reveals the size of the output signal at each instant of time for any specific input signal. The input signal is determined by its size at each instant of time; and for this reason, differential equations are said to be in the "time domain." Algebraic representation of a Laplace transform reveals the changes in size and timing between input signal and output signal at each frequency. Therefore, Laplace transforms are said to be in the "frequency domain."

The differential equation for the level process in Figure 34-1-2 describes the relationship between input and output of the level system.

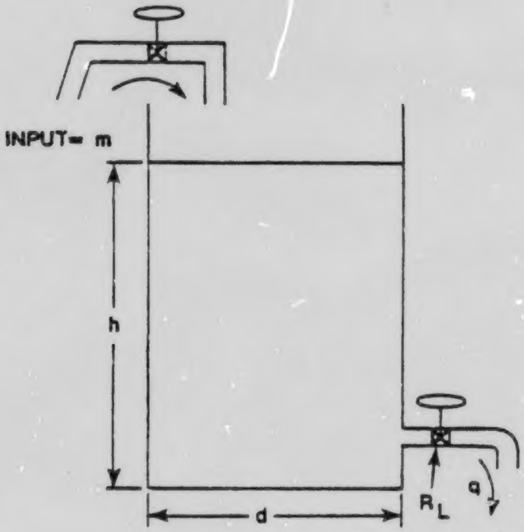


Figure 34-1-2. A liquid level process.

Equation 34-1-1 is the differential equation for the level process in Figure 34-1-2.

$$R_L C \frac{dh}{dt} + \frac{R_L}{\rho g} (m)$$

Equation 34-1-1.
(Equation = Eq.)

where:

R_L = laminar flow resistance measured in newton-seconds/meter^5.

C = capacitance of tank in $\frac{\text{cubic meters}}{\text{newton per sq meter}}$.

$\frac{dh}{dt}$ = change in level with respect to time.

h = liquid level in meters.

ρ = density of liquid in tank in kilograms/cubic meters.

$g = 9.81$ meters/second^2.

m = input flow rate in cubic meters/second.

EXAMPLE

Given: For the level process in Figure 34-1-2, the tank is empty before $t = 0$ seconds, and flow rate into the tank (m) = 0. Therefore, $h = m = 0$ when it is less than zero. At $t = 0$, m is increased to K cubic meters/seconds. (This is a step change in input.)

Find: Tank level after the step change in input.

Solution: For simplification, R_C is replaced by π, and $\frac{R_L}{\rho g}$ is replaced by A in the differential equation given for the level process:

$$\pi \frac{dh}{dt} + h = A\,m.$$

The level-process equation is in the time domain and, by Laplace transforms, is converted to the frequency domain. The following Laplace transform pairs are used for this transformation:

Time domain		Frequency domain
$m = k$	$\longrightarrow$	$m = k/s$
$\pi\, dh/dt$	$\longrightarrow$	πSH
h	$\longrightarrow$	H
Am	$\longrightarrow$	AM
$\pi\, dh/dt + h = Am$	$\longrightarrow$	$\pi SH + H = AM$

To solve the frequency domain equation for H, three algebraic operations are necessary. They are –

1. Substitute K/S for M in $\pi Sh + H = AM$ to get $\pi SH + H = \frac{AK}{S}$.
2. Factor H out of the left-hand side to get $H\ (\pi S + 1) = \frac{AK}{S}$.
3. Divide both sides by πSH to obtain –

$$H = \frac{AK}{S(\pi S + 1)}.$$

The problem now has been solved, but another transformation is necessary. The expression for H in Step 3 above is transformed back into the time domain by an inverse Laplace transform:

Time domain		Frequency domain
$h = AK(1 - e^{-\frac{t}{\pi}})$	$\longleftarrow$	$H = \frac{AK}{S(\pi S + 1)}$

The new expression in the time domain is now in an operating form; and by simple algebraic manipulation, a value for level (h) can be determined for any value of A, K, or t.

The preceding example illustrates use of Laplace transforms to determine specific properties of process variables that vary with time. More generally, however, the transfer function of a process can be expressed in the frequency domain input. The frequency-domain equation $\pi SH + H = AM$

can be solved for a ratio of output and input. The following steps will be used to solve the transfer function.

1. Give equation $\pi SH + H = AM$.
2. Factor H from the left-hand side:
   $$H\ (\pi S + 1) = AM.$$
3. Solve for H:
   $$H = \left(\frac{A}{\pi S + 1}\right) M.$$
4. Divide both sides by M:
   $$\frac{H}{M} = \frac{A}{\pi S + 1}.$$

This is the transfer function of the level process described.

The above transfer function contains three parameters — A, π, and S. A and π depend upon the resistance (R_L), the capacitance (C), and the liquid density (ρ) of the level process. For a given process, A and π are constant, and S is a function of the frequency of the input signal (M).

Transfer functions for other process and process characteristics can be found in the Reference Materials section of this module. For further explanation of these five functions, the student is referred to these references.

SIZE AND TIMING RELATIONSHIPS

Individual components of a closed-loop system affect the behavior of the system. The relationship between input and output is defined by the transfer function, which consists of two distinguishing factors. These factors are size and timing. Change in the size of the input signal is expressed as gain, and change in time or phase shift is timing relationship.

Four basic elements determine size and timing relationship between input and output:

- Resistance.
- Capacitance.
- Inertia.
- Dead time.

These elements are common to all types of systems because every system has a quantity of material, stored energy, or energy transfer capability that alters the input by a characteristic defined by the element of the system. There is an exact cause-and-effect pattern for a control system. The cause is the driving force, or potential, which is able to produce a distrubance in a process, and the reaction of the process as a result of the disturbance is the effect. A flow process is an example of the cause-and-effect pattern. Potential, or pressure, of the fluid within the line has the ability to produce a flow change, and the manner in which the flow changes with a change in pressure or pressure drop is the effect. Table 34-1-1 lists the driving force, the quantity, the change in quantity, and the standard unit of quantity measurement.

TABLE 34-1-1. PARAMETERS OF COMMON SYSTEMS AND CHANGE IN QUANTITY USED TO DEFINE RESISTANCE.

Type of System	Quantity	Potential	Quantity Change	Standard Units
Electrical	Charge	Voltage	Amount of charge transferred per second	Coulomb per second[1]
Liquid	Volume	Hydrostatic head	Amount of liquid transferred per second	Flow rate – cubic ft per second
Gas	Mass	Pressure	Amount of gas transferred per second	Flow rate – cubic ft per second
Thermal	Heat	Temperature	Amount of heat transferred per second	Flow rate – Btu per second
Mechanical	Displacement	Force	Distance traveled per second	Velocity – ft per second

[1] One coulomb is a number of electrons passing a point in a circuit.

RESISTANCE

"Resistance" is the term that describes opposition to the flow material or energy quantities. Resistance is present in different forms of each system and is measured in terms of the change in potential required to produce a change in a flow quantity per unit time. Electrical resistance is the opposition to current that results in a potential drop required to force the electrons through a resistive component. Gas flow resistance causes a pressure drop to produce a flow rate of gas through a fluid resistive element. Thermal resistance is the change in temperature required to produce a change in heat flow through a thermal resistive component. Mechanical resistance is a change in force required to produce a change in the velocity of a moving object.

Electrical Resistance

Electrical resistance is that property of a material that opposes or impedes the flow of electrons. Conductors of electrical current have low resistance, and insulators have a very high resistance. The unit of electrical resistance is expressed in ohms; and conductivity, which is the inverse of resistance, is measured in mhos. The relationship between the two units of measurement is –

$$\text{ohm} = \frac{1}{\text{mho}}; \qquad \text{mho} = \frac{1}{\text{ohm}}.$$

Equation 34-1-2 describes electrical resistance in terms of Ohm's law:

$$R = \frac{E}{I} = \frac{\Delta E}{\Delta I} \qquad \text{Eq. 34-1-2}$$

where:

R = electrical resistance in ohms.

E = electrical potential, or applied voltage, in volts.

I = resulting current, or flow of electrons, measured in amperes.

ΔE = a change in applied voltage.

ΔI = a corresponding change in current, measured in amperes.

Ohm's law is the equation of a straight line through the origin with a slope of R. As indicated by Figure 34-1-3, there is a corresponding change in current, regardless of the magnitude of change in voltage. The change in voltage divided by the change in current is equal to resistance, in accordance with Ohm's law. Because the volt-ampere graph in Figure 34-1-3 is linear, the electrical resistance is constant and is a function of the slope of the line.

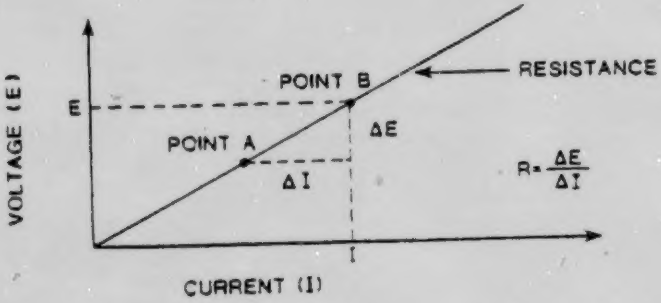


Figure 34-1-3. Voltage-current graph.

When resistive electrical components exhibit nonlinear characteristics, the volt-ampere graph will be curved. The resistance value will not be constant, but will change at different operating points. In such cases, resistance can be calculated from small changes of current produced by small changes in voltage – the assumption being that for small increments of the curve, resistance values are linear.

EXAMPLE

Given: A drop of ten volts across an electrical resistive component produces a current of 0.005 amperes.

Find: The value, in ohms, of the resistive component.

Solution: Use the Ohm's law relationship in Equation 34-1-2:

$$R = \frac{E}{I}$$

$$= \frac{10 \text{ volts}}{0.005 \text{ amperes}}$$

$$= 2000 \text{ ohms}$$

$$R = 2.0 \text{ K ohms.}$$

EXAMPLE

Given: A voltage change from 325 volts to 295 volts produces a current change from 26 amperes to 23.6 amperes.

Find: The electrical resistance of the circuit.

Solution: Use Equation 34-1-2:

$$R = \frac{\Delta E}{\Delta I}$$

$$= \frac{235 - 295}{26.0 - 23.6}$$

$$= \frac{30}{2.4}$$

$$R = 12.5 \text{ ohms}$$

Liquid Flow

Flow resistance is that property of a flow process that impedes the flow of a fluid. Flow resistive components are --

- Pipes.
- Valves.
- Restrictors: (1) differential producers for flow measurement and (2) restriction orifices for flow limiting.

Liquid flow resistance is determined by the relationship between a pressure drop across a restriction and the flow rate of the liquid through that restrictor. The two types of liquid flow are laminar and turbulent. Because each has a different liquid resistance to flow, there are two different flow equations. Laminar flow occurs when the liquid velocity is relatively low and when the velocity at the center of the pipe is considerably greater than that at the walls of the pipe. Velocity of the liquid flowing through a pipe is uniform and relatively high for turbulent flow.

The flow type, laminar or turbulent, depends upon four parameters:

- Liquid density (ρ).
- Inside diameter (D) of the pipe.
- Dynamic viscosity (μ) of the liquid.
- Average velocity of the flowing liquid.

These four parameters are grouped to express a dimensionless quantity called the "Reynolds number," which expresses the dynamic similarity of flow processes:

$$\text{Reynolds number} = \frac{\rho V D}{\mu}$$

When the Reynolds number is less than 2000, flow is laminar. For Reynolds-number values greater than 4000, flow is turbulent. Flow is transitional (neither laminar nor turbulent) for Reynolds-number values between 2000 and 4000.

Laminar Flow

Liquid laminar flow equations are as follows:

$$P = R_1 Q \qquad \text{Eq. 34-1-3}$$

$$R_l = \frac{128\ \mu \ell}{\pi D^4} \qquad \text{Eq. 34-1-4}$$

$$Q = \frac{\pi D^2 v}{4} \qquad \text{Eq. 34-1-5}$$

where:

R_l = laminar flow resistance, in $\frac{\text{newton-seconds}}{\text{meter}^5}$.

P = pressure drop across a restrictor, in $\frac{\text{newton}}{\text{SA meter}}$.

Q = fluid flow rate, in $\frac{\text{cubic meters}}{\text{second}}$.

μ = dynamic viscosity of the liquid, in $\frac{\text{newton-seconds}}{\text{SA meter}}$.

ℓ = pipe length, in meters.

v = average fluid viscosity, in $\frac{\text{meters}}{\text{second}}$.

D = inside diameter of the pipe, in meters.

Resistance for laminar flow is a constant that depends upon μ, ℓ, and D. The graph of the laminar flow equation is a straight line (Figure 34-1-4). The slope of the line is the laminar flow resistance R_l.

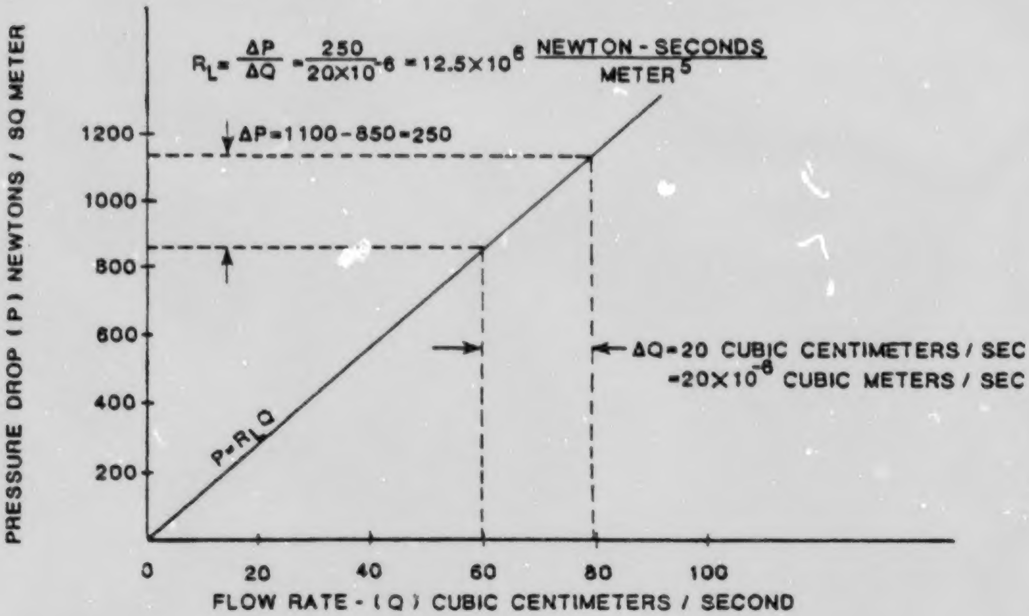


Figure 34-1-4. Pressure-versus-flow rate for laminar flow.

Turbulent Flow

Equations 34-1-6 through 34-1-9 are for liquid turbulent flow.

$$P = K_T Q^2 \qquad \text{Eq. 34-1-6}$$

$$R_T = 2K_T Q \qquad \text{Eq. 34-1-7}$$

$$K_T = \frac{8\rho f L}{\pi^2 D^5}$$ Eq. 34-1-8

$$Q = \frac{\pi D^2 v}{4}$$ Eq. 34-1-9

where:

R_T = turbulent flow resistance, in $\frac{\text{newton-seconds}}{\text{meter}^5}$.

P = pressure drop across a line restrictor, in $\frac{\text{newtons}}{\text{SA meter}}$.

K_T = turbulent flow constant.

Q = fluid flow rate, in $\frac{\text{cubic meter}}{\text{second}}$.

ρ = fluid density, in kilograms/cubic meter.

ℓ = pipe length, in meters.

D = inside pipe diameter, in meters.

f = friction factor, which is a dimensionless number that depends upon Reynolds number and internal pipe surface.

V = average velocity, in meters/second.

A plot of pressure drop against flow rate for turbulent flow similar to that for laminar flow in Figure 34-1-4 would show a nonlinear relationship because the pressure drop varies as the square of the flow rate (Eq. 34-1-1).

Gas-Flow Resistance

Gas-flow resistance is that property of flow processes that impedes the flow of gas. The principle of gas-flow resistance is similar to that of liquid-flow resistance. In laminar-flow applications, the pressure drop across a restrictor varies directly with the fluid velocity; but in turbulent flow, the pressure drop varies with the square of the fluid velocity. In gas-flow processes in nuclear plants, the flow usually is turbulent; and the equations that apply to turbulent flow commonly are used.

Gas resistance may be expressed in terms of a change in the upstream pressure of a flow resistrictor – or downstream – and is defined as "the change in pressure required to produce a unit change in mass flow rate."

Thermal Resistance

Thermal resistance is that property of a substance that impedes the flow of heat and is measured in terms of the change in temperatures required to produce a heat-flow rate through a heat-resistant material. A composite wall that separates two fluids at different temperatures is a heat barrier. Heat flows through the barrier as a function of temperature difference between the two sides (Equation 34-1-10).

$$Q = \frac{1}{R}(T_1 - T_2) \qquad \text{Eq. 34-1-10}$$

where:

Q = heat transfer, in watts.
R = thermal resistance of the barrier.
T_1 = higher temperature.
T_2 = lower temperature.

Determination of the values of R in Equation 34-1-10 for heat transfer is complex and beyond the scope of this module. The student is referred to reference sources for further study of this topic.

Mechanical Resistance

Mechanical resistance, or friction, is that property of a mechanical system that impedes mechanical motion. It is measured in terms of the change of force required to produce a unit change in the velocity of displacement of an object.

A common application utilizing mechanical friction is a dashpot used in many process instruments to dampen mechanical motion. The cylinder in the dashpot illustrated in Figure 34-1-5 is stationary, and the piston is connected to the moving part by the piston rod. When movement is encountered, fluid in the cylinder is displaced and must move through the small opening between the piston and the cylinder. Flow rate of the fluid through the restrictor is proportional to the velocity of the moving part (M). The pressure drop across the piston ($P_2 - P_1$) is required to produce the fluid flow through the restrictor. This pressure difference produces a restraining force that is equal to the difference in pressure times the area of the piston: $F = (P_2 - P_1)A$.

When fluid flow rate through the restriction is small, flow is laminar; and the force is proportional to the fluid velocity. When flow rate is large, flow is turbulent; and the force is proportional to the square of the velocity. Mechanical resistance that produces a force proportional to velocity is called "viscous friction"; the type that produces a force independent of velocity is termed "coulomb friction."

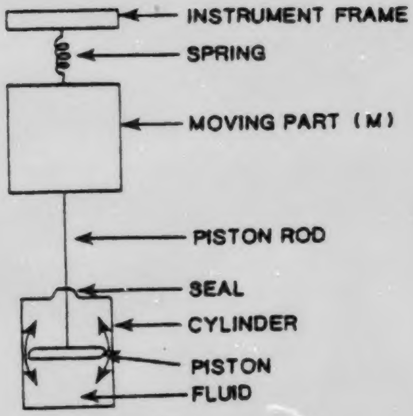

INSTRUMENT FRAME
SPRING
MOVING PART (M)
PISTON ROD
SEAL
CYLINDER
PISTON
FLUID

Figure 34-1-5. Mechanical resistance provided by a dashpot.

The equations for mechanical resistance are –

$$R_1 = \frac{F}{v}$$ Eq. 34-1-11

$$R_2 = \frac{dF}{dv}$$ Eq. 34-1-12

$$R_3 = \frac{\Delta F}{\Delta v}$$ Eq. 34-1-13

where:

R_1 = resistance of dashpots with laminar flow, in newton-seconds/meter.

R_2 = resistance of dashpots with turbulent flow, in newton-seconds/meter.

R_3 = resistance of dashpots with coulomb and viscous friction, in newton-seconds/meter.

F = force, in newtons.

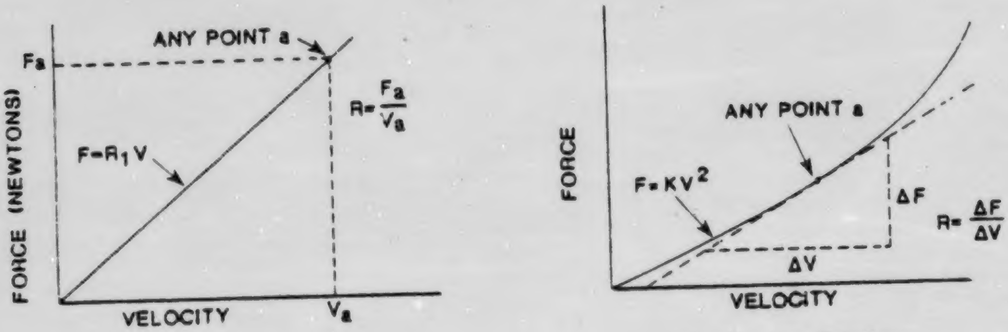
v = velocity, in meters/second.

ΔF = change in force between two points of the F versus v curve.

Δv = change in the velocity between the same two points.

$\frac{dF}{dv}$ = slope of the F versus v curve.

The curves in Figure 34-1-6 represent force-to-velocity relationships of viscous and coulomb friction.



(a) Viscous Friction

(b) Coulomb Friction

Figure 34-1-6. Mechanical resistance.

EXAMPLE

Given: A dashpot used for mechanical damping in a transmitting instrument produces laminar flow. A test indicated that a force of 69 newtons produced a fluid velocity in the dashpot of 38 meters/second.

Find: Mechanical resistance provided by the dashpot.

Solution: Since the flow is laminar, Equation 34-1-11 will be employed:

$$R_1 = \frac{F}{v}$$

$$= \frac{69}{38}$$

$$R = 1.81 \text{ newton-seconds/meter.}$$

CAPACITANCE

Capacitance is the quantity of material, energy, or distance required to produce a unit change in potential. Capacitance is a dynamic quantity that expresses the relationship between a change in quantity and a corresponding change in potential. Capacity is the total material or energy-storing ability of a process and should not be confused with capacitance. Two level processes can have the same capacity (gallons) and have different capacitance (gallons/feet of level).

Electrical Capacitance

Electrical capacitance is the quantity of electrical charge required to make a unit change in electrical potential. The unit of electrical capacitance is the farad. Equation 34-1-14 expresses the electrical capacitance relationship.

$$C_E = \frac{\Delta q}{\Delta e} \qquad \text{Eq. 34-1-14}$$

where:

C_E = capacitance, in farads.

Δq = a change in electrical charge, in coulombs.

Δe = a change in electrical potential, in volts.

By simple mathematical manipulation of the capacitance equation, $\Delta q = C\Delta e$; and division of both sides by t (time) $\frac{\Delta q}{t} = \frac{C\Delta e}{t} = I$, where Δt = time (seconds) required to make the Δq change in charge and where I = the average current (in amperes) during the time interval Δt. When Δt approaches zero, $\Delta q/\Delta t$ is dq/dt, which is the instantaneous rate of charge change. Likewise, $\Delta e/\Delta t$ becomes de/dt, which is the instantaneous rate of potential change. Then $\frac{dq}{dt} = I = C\frac{de}{dt}$, where I is the instantaneous current.

EXAMPLE

Given: A current of 0.005 amperes and time duration of 0.5 seconds is applied to an electrical capacitor. Voltage across the capacitor is charged to 50 volts.

Find: Capacitance of the capacitor.

Solution: Use $I = C \frac{de}{dt}$ as derived from Equation 34-1-14:

$$I = C \frac{de}{dt}$$

$$0.005 = \frac{50}{0.5} (C)$$

$$C = (0.005) \frac{0.5}{50}$$

$$= 0.00005 \text{ farads}$$

$$C = 50 \times 10^{-6} \text{ farads.}$$

Liquid Capacitance

Liquid capacitance is defined in terms of a volume change of liquid (in a tank) required to produce a change in the hydrostatic head of the bottom, or reference point, of the tank or in the level measured in distance. Liquid capacitance is stated mathematically in the form of Equation 34-1-15.

$$C_L = \frac{\Delta V}{\Delta P} \qquad \text{Eq. 34-1-15}$$

where:

C_L = liquid capacitance.

ΔV = change in volume, in cubic meters.

ΔP = corresponding change in pressure, in newtons/square meters.

This general equation is reduced to the working equation (Equation 34-1-16) for liquid capacitance.

$$C_L = \frac{A}{\rho g} \qquad \text{Eq. 34-1-16}$$

where:

C_L = liquid capacitance, in $\frac{\text{cubic meters}}{\text{newtons per square meter}}$.

A = cross sectional area of the bottom of the tank, in square meters.

ρ = density of liquid, in kilograms/cubic meter.

g = 9.81 meters/second^2.

EXAMPLE

Given:	A cylindrical tank with a diameter of 2.6 meters and a height of 4 meters.
Find:	Capacitance of the tank when it is filled with kerosene (ρ = 800 kg/m^3).
Solution:	Calculate from Equation 34-1-16, rearranging as required.

$$C_L = \frac{A}{\rho g}$$

$$A = \frac{\pi D^2}{4}$$

$$g = 9.81 \text{ meters/second}^2$$

$$C = \frac{\frac{(3.14)\ (26)^2}{4}}{(800)\ (9.81)} = \frac{5.30}{7848} = 0.000675$$

$C = 6.75 \times 10^{-4}$ cubic meters/newton per sq meter.

Gas Capacitance

Gas capacitance is defined in terms of change in the mass of a gas (in a pressure vessel) required to produce a unit change in pressure while the temperature is constant. The ideal gas law (Equation 34-1-17) can be used to determine the capacitance.

$$PV = nRT = 1 \qquad \text{Eq. 34-1-17}$$

where:

P = absolute pressure of the gas in newtons/meter^2.
V = volume of gas in cubic meters.
$n = \frac{10^3\ m}{M}$
m = mass of the gas in kilograms.
M = molecular weight of gas.
R = universal gas constant = 8.314 joule/k-mole.
T = absolute temperature in Kelvin.

By substitution of the value for n into the above equation $PV = \frac{10^3 m}{M} RT$ and solving for m, mass of the gas –

$$m = [1.2 \times 10^{-4} M (\frac{V}{T})]P.$$

This equation applies to a pressure vessel, where V is volume, T is temperature, and M is molecular weight. When M, V, and T terms are held constant, the terms within the bracket are constant, and gas capacitance, which is the relationship between a change in mass and a corresponding change in pressure, is determined by Equation 34-1-18.

$$C_G = 1.2 \times 10^{-4} \frac{MV}{T} \qquad \text{Eq. 34-1-18}$$

where:

C_G = gas capacitance in kilograms/newton per meter².
M = molecular weight of gas.
V = volume of pressure vessel in cubic meters.
T = gas temperature, in Kelvin.

EXAMPLE

Given: A pressure tank with a volume of 200 cubic meters filled with carbon dioxide (M = 44). The temperature is 50°C.

Find: Capacitance of the tank.

Solution: Employ Equation 34-1-18:

$$C_G = 1.2 \times 10^{-4} \frac{MV}{T}$$

$$= \frac{1.2 \times 10^{-4} (44) (200)}{273 + 50^{\circ}}$$

$$= \frac{10.656}{323}$$

$$= 329.9$$

C_G = 329.9 kilograms/newton per meter².

Thermal Capacitance

Thermal capacitance is defined in terms of the change in heat required to produce a unit change in temperature. The specific heat of a substance is the heat energy required to change the temperature of one kilogram of the material 1° Kelvin. Thermal capacitance of a material is simply the product of the specific heat and the mass of the material (Equation 34-1-19).

$$C_T = mS_R \qquad \text{Eq. 34-1-19}$$

where:

C_T = thermal capacitance, in joule/Kelvin.
m = mass of material, in kilograms.
S_R = specific heat, in joule/kilogram-Kelvin.

Mechanical Capacitance

Mechanical capacitance (Equation 34-1-20) is defined as the change in the displacement of a spring required to make a unit change in force. The spring constant is the reciprocal of the capacitance.

$$C_M = \frac{\Delta X}{\Delta F} = \frac{1}{K} \qquad \text{Eq. 34-1-20}$$

where:

C_M = mechanical capacitance, in meters/newton.
K = spring constant, in newtons/meters.
ΔX = change in deflection, in meters.
ΔF = corresponding change in force, in newtons.

EXAMPLE

Given: A force of 1000 newtons compresses a spring by 75 centimeters.

Find: Mechanical capacitance and spring constant.

Solution: From Equation 34-1-20 —

$$C = \frac{\Delta X}{\Delta F}, \text{ and } K = \frac{1}{C}$$

$$= \frac{0.75}{1000}$$

$$C = 0.00075 \text{ meters/newton}$$

$$K = \frac{1}{C}$$

$$= \frac{1}{0.00075}$$

$$K = 1333.33 \text{ newtons/meter.}$$

INERTIA, INERTANCE, AND INDUCTANCE

Inertia is measured in terms of the potential required to produce a unit change in the flow rate of a quantity per unit time. This property is important in electrical systems and is known as "inductance." In fluid systems, the term "inertance" is used to describe the property; and the term is "inertia" in mechanical systems.

Electrical Inductance

Electrical inductance is measured in terms of voltage required to cause a current change of 1 ampere per second through an inductor. The inductance equation is –

$$E = L\left(\frac{\Delta I}{\Delta t}\right) \qquad \text{Eq. 34-1-21}$$

where:

E = electrical potential, in volts.
L = inductance, in henrys.
ΔI = change in electrical current, in amperes.
Δt = time required for Δi to occur, in seconds.

One volt will be generated across a 1-henry inductor (coil) when current through the coil is changing at the rate of 1 ampere per second. Voltage generated by an inductor exhibits a polarity that opposes the voltage that produced the current. For this reason, voltage produced by an inductor is known as "Counter," or "Back," EMF.

EXAMPLE

Given: Current is changing through a 2-henry coil at the rate of 3 amperes/0.001 second.

Find: The voltage, or counter EMF (CEMF), developed across the coil.

Solution: From Equation 34-1-21 –

$$E = L\left(\frac{\Delta I}{\Delta t}\right)$$

$$= \frac{2(3\text{ amperes})}{(0.001\text{ second})} = \frac{2\ (3)}{0.001}$$

$$= 6 \times 10^3$$

$$= 6000\text{ volts.}$$

Mechanical Inertia (Mass)

Mechanical inertia is measured in terms of the force required to produce a unit change in acceleration. The term "mass" is used to describe the inertia element of a mechanical system. The mechanical inertia formula is:

$$F = M \left(\frac{\Delta v}{\Delta t}\right) \qquad \text{Eq. 34-1-22}$$

where:

F = force, in newtons.

M = mass, in kilograms.

Δv = change in velocity produced by F, measured in meters/second.

Δt = time required for Δv to occur, measured in seconds.

EXAMPLE

Given: An object has a mass of 2000 kilograms and is accelerated from 0 to 100 meters/second in 10 seconds.

Find: The force required to produce the acceleration.

Solution: Use Equation 34-1-22:

$$F = M \left(\frac{\Delta v}{\Delta t}\right)$$

$$= 2000 \text{ kilograms} \left(\frac{100 \text{ meters}}{10 \text{ seconds}}\right)$$

$$F = 20{,}000 \text{ newtons}.$$

Fluid Flow Inertance

Fluid inertance is measured in terms of the pressure drop between two points in a pipe required to produce a unit change in flow measurement per unit time. The pressure drop acting on the cross-sectional area of the pipe produces a force F equal to the pressure drop P times the area A (Equation 34-1-23).

$$F = PA \qquad \text{Eq. 34-1-23}$$

This force will cause the fluid to accelerate between two points in accordance with Newton's law of motion.

The general working equation for flow inertance is –

$$I = \rho \left(\frac{L}{A}\right) \qquad \text{Eq. 34-1-24}$$

where:

I = inertance, in $\frac{\text{newton per square meter}}{\text{cubic meter per second}^2}$.

P = pressure drop between two points in the pipe, in newtons/square meter.

ρ = fluid density, in kilograms per cubic meter.

L = distance between the two pressure points on the pipe, in meters.

A = cross-sectional area of pipe, in square meters.

Q = flow rate of fluid, in cubic meters per second.

ΔQ = a change in flow rate produced by the pressure drop P, in cubic meters per second.

Δt = time required for Δt to occur, in seconds.

$\frac{\Delta Q}{\Delta t}$ = rate of change of liquid flow rate, in cubic meters per second.

EXAMPLE

Given: Pipe diameter = 10 cm.
Distance between pressure taps = L = 150 M.
Flowing fluid is water, p = 1000 kilogram/cubic meter.

Find: Liquid flow inertance.

Solution: From the fluid-flow inertance equation —

$$I = \rho \left(\frac{L}{A}\right)$$

Cross-sectional area of the pipe is —

$$A = \frac{\pi D^2}{4}$$

$$= \frac{3.14\ (100\ \text{cm}^2)}{4}$$

$$A = 78.5\ \text{cm}^2$$

$$I = 1000\ \text{kilograms/cubic meter}\ \left(\frac{150\ \text{meters}}{78.5\ \text{cm}^2}\right)$$

$$I = 1910.8\ \frac{\text{newtons per meter}^2}{\text{cubic meters per second}^2}$$

DEAD TIME

Dead time is the interval between the time at which a signal appears at the input of a component and the time at which a corresponding response occurs at the output. In most processes in a nuclear power plant, the input signal is changed in magnitude as well as time. If the input signal is changed only in time, a pure dead time element exists. The dead time element results from time lost, or time required to transport material or energy from one point in the process to another point. These two points normally are input and output. The dead time element is the most difficult control characteristic of a process.

When velocity of the material or energy being transferred is V and distance traveled is D, the following relationship exists:

$$t_d = \frac{D}{V} \qquad \text{Eq. 34-1-25}$$

where:

t_d = dead time, in seconds.
D = distance between input and output, in meters.
v = velocity of material or energy being transferred, in meters/second.

The effect of dead time is to delay the input signal in such a manner that the output occurs at a time after the input. This time interval between input and output is dead time. (t_d). When the input signal is $f_i(t)$ and the output signal is $f_o(t)$, then t is the symbol that indicates that f_i and f_o have different values at different times. If $f_i(t)$ is 5 at $t = 0$, then $f_o(t)$ will be 5 at $t = 5$ seconds. This simply indicates that input and output are shifted in time (phase) by 5 seconds. Any signal on the input at $t = 0$ will appear at the output at $t = 5$ seconds. If the phase shift between the input and output is 5 seconds, then $f_o(t) = f_i(t - 5)$, or, generally stated, $f_o(t) = f_i(t - t_o)$. This equation is known as the "dead time equation" and represents a dead time process. It is significant to note that the output is the same as the input was at t_o seconds before t.

Electrical Dead Time

Applications in process instrumentation in nuclear power plants are not affected by dead time in electrical signals. Velocity of propagation of electrical signals is so great (about 3 x 10^8 meters per second) and the distance path of transmitted signals is so relatively short (usually less than 1 kilometer) that the dead time is negligible. Transmission time of electrical signals is very short compared to the response time of most processes.

In some computer applications, however, a delay in a transmission line sometimes is used deliberately to perform desired logic functions. For this reason, an understanding of the dead time in electrical signal transmission is necessary.

Equation 34-1-26 (which is very similar to Equation 34-1-25) is utilized in the computation of dead time in electrical circuits.

$$t_d = \frac{D}{v_p} \qquad \text{Eq. 34-1-26}$$

where:

v_p = velocity of propagation of an electrical signal, in meters/second.

EXAMPLE

Given: D = 900 kilometers, the length of a transmission line.

Find: Dead time in the signal transmission.

Solution: From the dead time formula

$$
\begin{aligned}
t_d &= \frac{D}{v_p} \\
&= \frac{900 \text{ meters}}{2.8 \times 10^{8} \text{ meters/second}} \\
&= 321 \times 10^{-8} \text{ seconds} \\
&= 3.24 \times 10^{-6} \text{ seconds} \\
t_d &= 3.24 \text{ microseconds.}
\end{aligned}
$$

Solid Flow Rate Dead Time

An example of solid flow rate dead time is a conveyor belt that transports solid material through some distance. The dead time involved in this application is that required for the material to travel from the inlet end to the outlet end. This is a function of velocity of the belt and can be determined from the dead time formula in the preceding Example.

Liquid Flow Rate Dead Time

Dead time in a liquid flow process is similar to that of a solid flow process, as it is the time required to transport the liquid from one point of the pipe to another point.

The equation for liquid flow dead time is basically the same as used in the preceding Example. The fluid velocity can be determined from the flow rate by the following Equation:

$$v = \frac{Q}{A} = \frac{4Q}{\pi d^2} \qquad \text{Eq. 34-1-26}$$

where:

v = average velocity of fluid, in meters/second.
Q = flow rate, in cubic meters/second.
A = area of pipe, in square meters.
d = inside diameter of pipe, in meters.

EXERCISES

1. List and define the four basic elements that determine the characteristics of a process.
2. Given: A mechanical dashpot with laminar flow requires a force of 30 newtons to produce a velocity of 18 meters/sec of the piston.
   Find: Mechanical resistance provided by the dashpot.
3. Given: A current through an inductor changing at a rate of 0.001 amperes per second produces 0.5 volts of counter EMF.
   Find: Value of the inductor.
4. Given: An automobile weighs 3800 kilograms and is accelerated to a speed of 80 meters/second from rest position in 16 seconds.
   Find: Force required to produce this acceleration.

PROCEDURES

None.

MATERIALS

None.

DATA TABLE

None.

REFERENCE MATERIALS

Bateson, Robert. Introduction to Control System Technology. Columbus, OH: Merrill Publishing Company, 1973.

Johnson, Curtis D. Process Control Instrumentation Technology. New York: John Wiley & Sons, 1977.

TEST

1. Define transfer function, and explain its use.

2. What are Laplace transforms?

3. Why are Laplace transforms employed in process analysis?

4. Define the following terms:

   a. Inertia.

b. Inductance.

c. Inertance.

d. Capacitance (the three types).

e. Dead time (the three types.)

f. Resistance (the three types).

5. Write the equation for, and explain the terms used to calculate the quantities as listed in Test item 4.

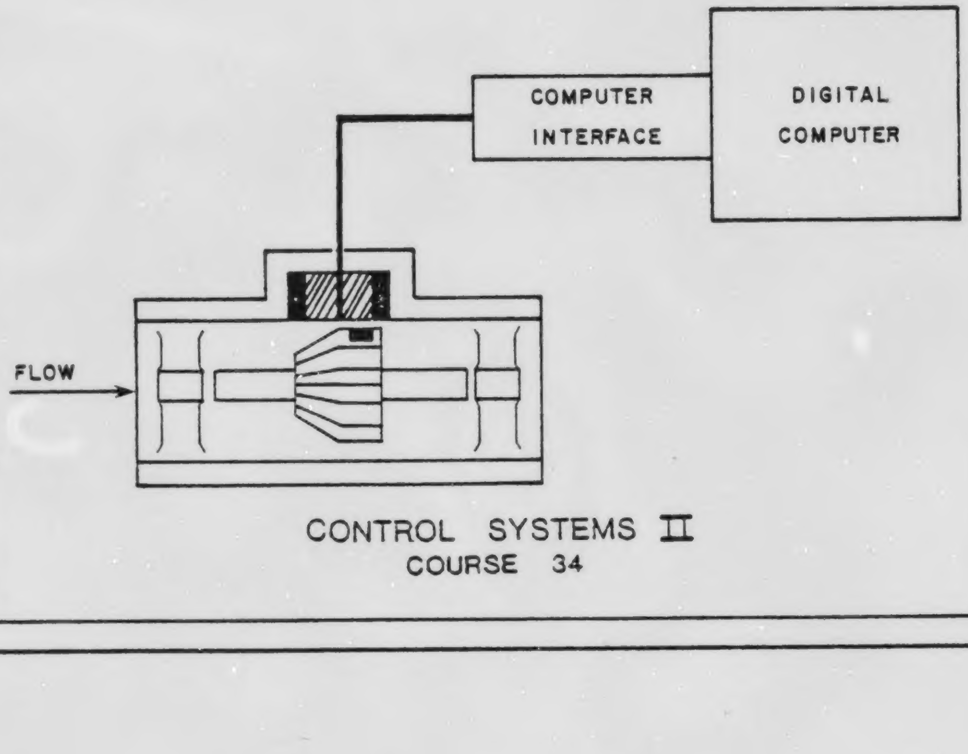
6. What is frequency domain?

7. What is time domain?

NUCLEAR TECHNOLOGY

MODULE 34-2

FREQUENCY RESPONSE ANALYSIS


COMPUTER INTERFACE
DIGITAL COMPUTER
FLOW

CONTROL SYSTEMS II
COURSE 34

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

COURSE MODULES

CONTENTS

COURSE 34 CONTROL SYSTEMS II

MODULE 34-1 Introduction to Transfer Functions
⇨ MODULE 34-2 Frequency Response Analysis
MODULE 34-3 Combination Control Systems
MODULE 34-4 Controller Tuning
MODULE 34-5 Operational Amplifiers
MODULE 34-6 Microprocessor Utilization
MODULE 34-7 Microprocessor Programming

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INTRODUCTION

In the design and application of control systems, many components are connected by electronic or pneumatic signal paths. The significant changes of the signals as they travel through the components are magnitude and timing. The system – whether very simple, with only one component, or complex, utilizing several components – can be defined best when the change brought about on the signal is understood.

The most exact method for analysis of the dynamic response of a system that utilizes several components is the frequency response method. When convenient and applicable, frequency response analysis is performed by experimental observation. For other situations in which this is not a practical approach, analytical methods can be employed to evaluate the dynamic properties of a system.

MODULE PREREQUISITES

The student should have completed Course 3, "Principles of Process Instrumentation"; Course 6, "Instrumentation and Control of Reactors and Plant Systems"; Course 33, "Control Systems I"; and Module 34-1, "Introduction to Transfer Functions."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
    - Frequency response analysis.
    - System gain ratio.
    - System phase shift.
    - Bode plot.
2. List and explain two methods by which frequency analysis is performed.
3. List an advantage and a disadvantage of each method in Objective 2.
4. Describe the principles of process design by frequency analysis for simple- and multiple-component processes.
5. Construct a Bode plot.
6. Discuss the principles of controller design by frequency analysis.
7. Given the frequency domain equation for a first-order lag component, the time constant, and frequency of the input, calculate frequency response.

FEEDBACK PRINCIPLES OF CONTROL

Most control systems in nuclear facilities are of the feedback type. This method of control consists of the elements represented in Figure 34-2-1. A process or plant that is controlled usually has several inputs and outputs.

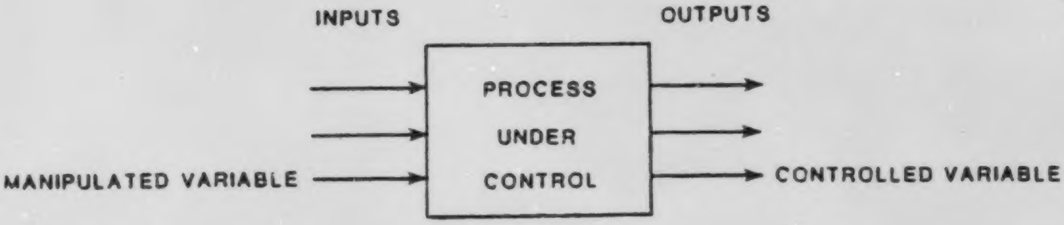

INPUTS
OUTPUTS
PROCESS
UNDER
CONTROL
MANIPULATED VARIABLE
CONTROLLED VARIABLE

Figure 34-2-1. A controlled process with three inputs and three outputs.

For feedback control application, one of the inputs will be manipulated (regulated) to maintain an exact condition or quantity in one of the outputs. This controlled output is known as the "controlled variable." A level process with inputs and outputs is illustrated in Figure 34-2-2.

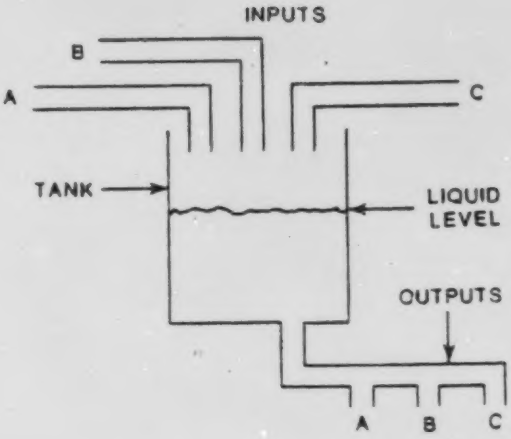

INPUTS
B
A
C
TANK
LIQUID LEVEL
OUTPUTS
A
B
C

Figure 34-2-2. A level process with multiple inputs and outputs.

To control the level in the tank of Figure 34-2-2, the sum of the inputs (A + B + C) must equal the sum of the outputs (A + B + C). This statement conforms to the definition of the purpose of a control system; that is, to maintain a balance between the supply (inputs) and demand (outputs) of a process (the tank). If all inputs and outputs are constant, the level will remain at a constant value, and the task of controlling the level process will be achieved. This condition seldom is present in an actual control situation, however.

Normally, at least one, usually several, of the inputs change at uncontrolled rates. The uncontrolled inputs are called "disturbance variables." The one input selected to be manipulated to maintain a balance between the inputs and outputs is the "manipulated variable." In practice, many of the disturbance variables cannot be measured or altered. The effect of the disturbance variables will not be known until the process has changed.

To minimize the effect that disturbance variables have on the process, the controlled variable of the process is measured and compared to a "reference variable." The difference between the measured variable and the reference variable is an error signal that is scaled and used to change the manipulated variable. The new level of manipulated variable must be just enough to compensate for the variation in disturbance variable that produced the error signal.

In feedback control applications, the automatic feedback controller closes the loop between the process change produced by the disturbance variable and the manipulated variable adjustment necessary to compensate for the disturbance variable. The feedback link that allows the controller to close the loop is provided by process measurement and is fundamental to automatic feedback control; the controller otherwise would have no reference for control in relation to the process. An automatic feedback control system is depicted in Figure 34-2-3.

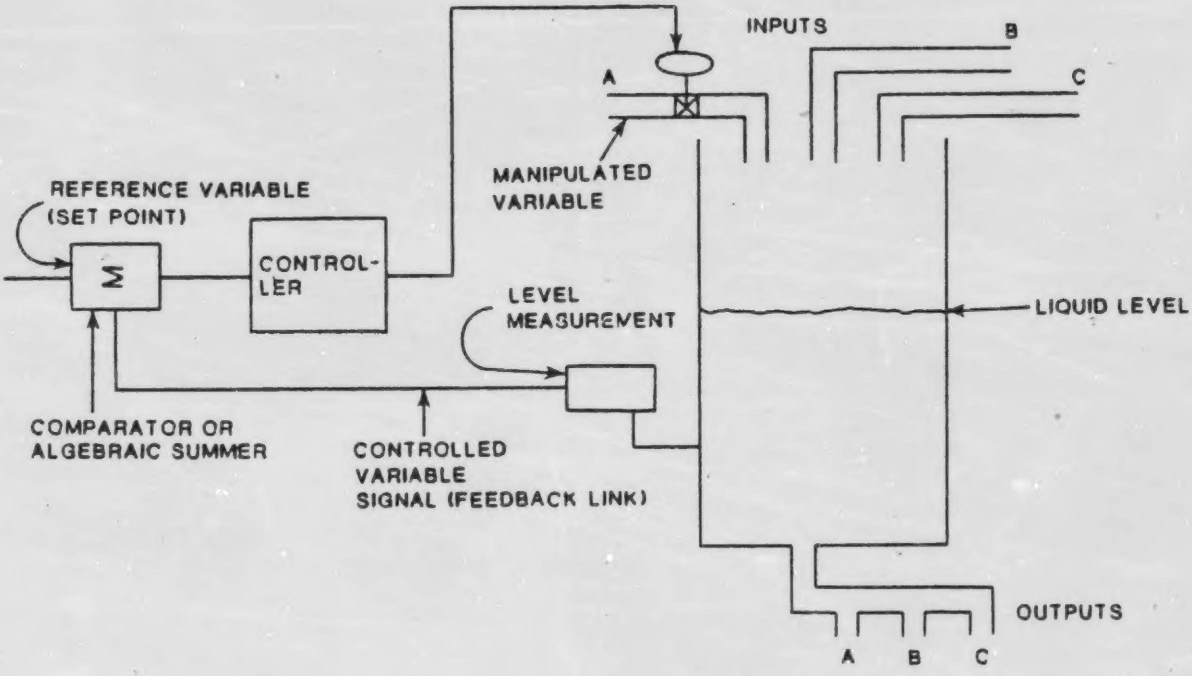

INPUTS
A
B
C
MANIPULATED VARIABLE
REFERENCE VARIABLE (SET POINT)
Σ
CONTROL-LER
LEVEL MEASUREMENT
LIQUID LEVEL
COMPARATOR OR ALGEBRAIC SUMMER
CONTROLLED VARIABLE SIGNAL (FEEDBACK LINK)
OUTPUTS
A
B
C

Figure 34-2-3. An automatic feedback control system.

From the previous discussion and observation of the system in Figure 34-2-3, it should be clear that a change in the manipulated variable will occur only after a change in disturbance variable has resulted in a change in level. The level change is measured by the level-measurement transmitter, which generates a signal proportional to the level change that is compared to the reference variable to produce an error signal. The controller acts on the error signal to produce an output that alters the manipulated variable by an amount equal in magnitude and opposite in direction to the disturbance variable that first caused the level to change. Before the manipulated variable can be altered, the medium to be controlled (level, in this discussion) first must change. To overcome this undesirable characteristic of all feedback control systems, the feedback controller can achieve optimum control of a process only when it regulates the manipulated variable at an amount and rate that will offset the effects caused by the disturbance variable. This best can be accomplished when the dynamic properties of both the process and control system components can be analyzed and characterized. Frequency response analysis is a means of providing such analysis.

FREQUENCY-RESPONSE ANALYSIS

Two important dynamic properties of a process that must be considered in the design and application of a control system are the gain and phase relationship between the input and corresponding output. These relationships are defined by the transfer function of the system. The gain characteristic is the ratio of the magnitude of the output signal divided by the magnitude of the input signal. To avoid the confusion that often results from use of scaled signals that correspond to different units, the gain is expressed as a ratio of a percentage of the full-scale or span of the signal (Equation 34-2-1).

$$\text{Gain} = \frac{\text{Output (percent)}}{\text{Input (percent)}} \qquad \text{Equation 34-2-1}$$

(Equation = Eq.)

Change in the timing relationship of input and output signals is expressed in degrees and normally is referred to as the "phase angle" or "phase difference" between the two signals. Figure 34-2-4 represents the input and output of a system and defines the system gain and phase shift. The characteristics of a system will be revealed by the relationship between input and output with respect to gain and phase shift. A sinusoidal input is employed in this analysis because the waveforms will not be distorted by the system being analyzed. The input of a linear system will produce a sine wave output that will be altered only in magnitude and time.

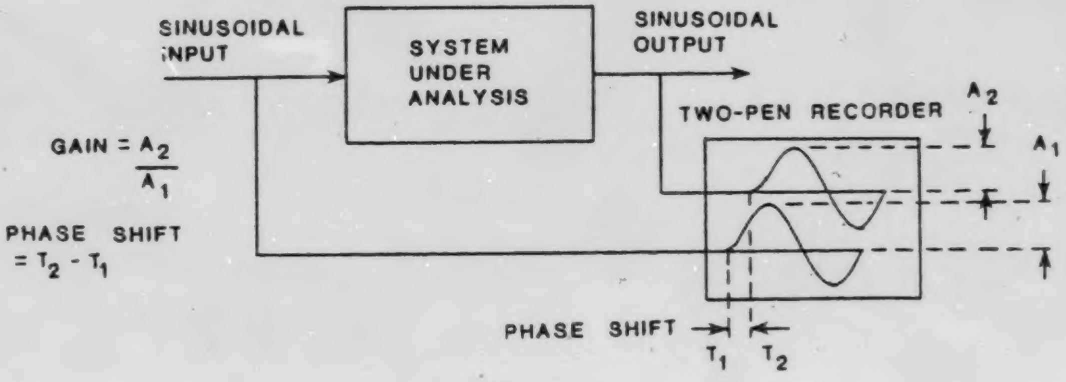

SINUSOIDAL INPUT
SYSTEM UNDER ANALYSIS
SINUSOIDAL OUTPUT
TWO-PEN RECORDER
A_2
A_1
GAIN = $\frac{A_2}{A_1}$
PHASE SHIFT = $T_2 - T_1$
PHASE SHIFT
T_1
T_2

Figure 34-2-4. Determination of amplitude ratio (gain) and phase shift of a system.

The frequency response of a component or a series of components as would be found in a multicomponent system is the set of gain values and phase differences for a range of frequencies. For each separate frequency, there is a gain and a phase difference that gives the characteristic response of the system at that particular frequency. For several different frequencies, the different responses are plotted on pairs of graphs, which show the gain and phase shift for each frequency. These graphs are known as "Bode plots." When interpreted properly, a Bode plot can provide all information needed to simulate, design, and operate a system. A fundamental basis of the frequency response method of analysis is the fact that the plot is a "fingerprint" characteristic of the system's dynamic performance. Each component part of the system has an individual frequency-response characteristic that determines the frequency-response characteristic of the total system. When any part of the system is altered, the total system response is changed. The response of the system in Figure 34-2-3 is determined by the response of the valve, transmitter, controller, and process.

DETERMINATION OF FREQUENCY RESPONSE

Two methods can be used to determine the frequency response of a system — experimental and analytical. In the experimental method, a sinusoidal input is applied to the input. The output signal is measured and compared to the input in magnitude and phase angle. This procedure sometimes is difficult because the equipment must be selected carefully in order that the response of the component is not altered. The experimental method may not be practical in some processes because of the instability introduced into the system. These systems must be studied by analytical means.

Experimental Method for Analysis of a Liquid-Level Process

In the liquid-level process of Figure 34-2-5, water is in an open tank at constant head pressure. Water from the open tank flows through a control valve to another

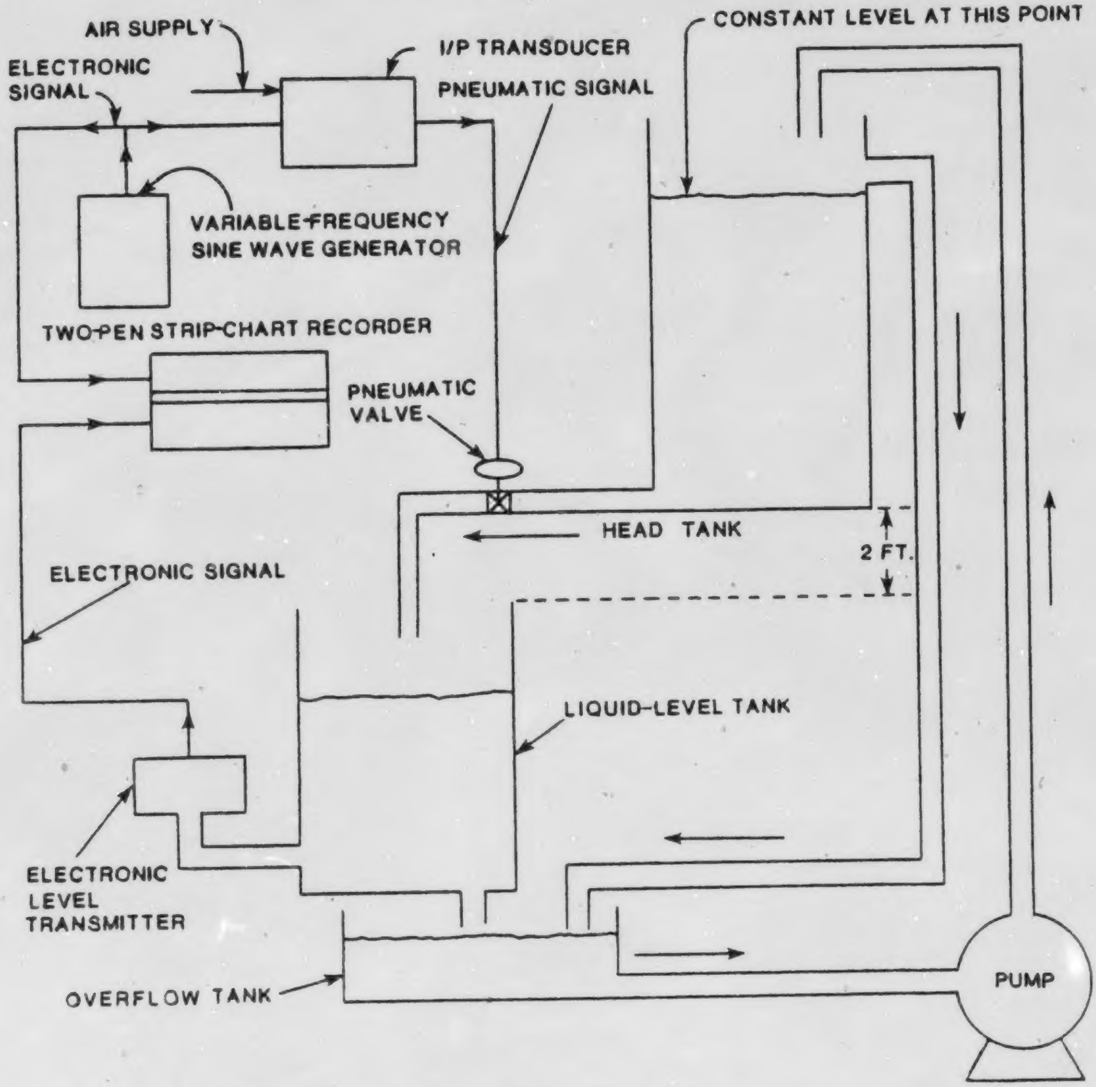

AIR SUPPLY
ELECTRONIC SIGNAL
I/P TRANSDUCER
PNEUMATIC SIGNAL
CONSTANT LEVEL AT THIS POINT
VARIABLE-FREQUENCY SINE WAVE GENERATOR
TWO-PEN STRIP-CHART RECORDER
PNEUMATIC VALVE
HEAD TANK
2 FT.
ELECTRONIC SIGNAL
LIQUID-LEVEL TANK
ELECTRONIC LEVEL TRANSMITTER
OVERFLOW TANK
PUMP

Figure 34-2-5. A liquid-level process for frequency response analysis.

liquid-level tank. Water from the liquid-level tank flows into an overflow tank with the overflow from the head tank and is pumped back into the head tank. The valve is positioned by a sinusoidal signal from an electrical sine-wave generator. This signal is converted to a pneumatic signal by a current-to-pneumatic (I/P) transducer. The level in the liquid-level tank is measured by an electronic level transducer and recorded on a daul-pen strip-chart recorder, along with the signal applied to the valve.

A frequency response analysis of the level process depicted in Figure 34-2-5 is performed by establishment of flow rates and levels at very low-frequency or steady-state values. When the frequency applied to the control valve is very low, there is no phase shift between the two signals on the recorder. The process in this situation is following the valve operation. The level can change as quickly as the valve. The pattern on the two-pen recorder will be an in-phase response (Figure 34-2-6). Amplitude ratio of the two signals is one at this frequency.

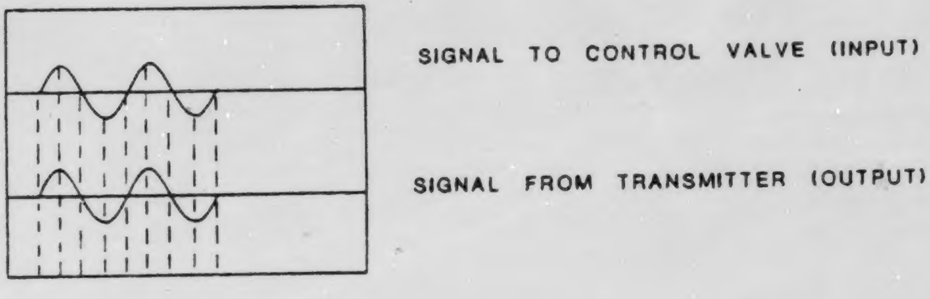
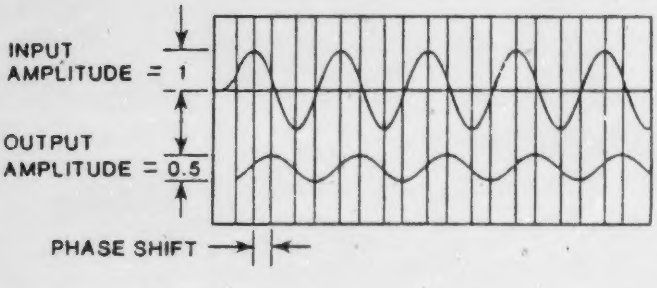

SIGNAL TO CONTROL VALVE (INPUT)
SIGNAL FROM TRANSMITTER (OUTPUT)

Figure 34-2-6. In-phase relationship between input and output at low frequencies.

When input frequency is increased by adjustment of the sine-wave generator, the magnitude of the level change becomes less; and a definite phase shift between input and output can be observed. However, the sine-wave signal has not been distorted, but shifted, in time.

Data for a Bode plot can be obtained by increasing of the input frequency at small increments and observation of the amplitude ratio and phase shift for each frequency. Phase shift will increase, and amplitude ratio will decrease as frequency increases. The relationship between input and output at a high frequency is presented in Figure 34-2-7. Frequency of the input signal can be increased to a maximum value until the phase shift reaches 90°: This is the maximum phase shift for a single-capacity system. The one liquid-level tank used in the example represents the single capacity because as the inflow increases to the point at which it exceeds the outflow, the level will start to increase. Likewise, when inflow falls below outflow, the level must start to fall.



$$\text{AMPLITUDE RATIO} = \frac{0.5}{1} = 0.5$$

$$\text{THE PHASE SHIFT} = \frac{1 \text{ DIVISION}}{4 \text{ DIVISIONS}/\text{CYCLE}} \times \left(360^\circ/\text{CYCLE}\right)$$

$$\left(\frac{1}{4} \text{ DIVISIONS}\right)\left(\frac{\text{CYCLE}}{\text{DIVISIONS}}\right)$$

$$\left(360^\circ/\text{CYCLE}\right)$$

$$= 90^\circ$$

Figure 34-2-7. The phase shift and amplitude ratio at a higher frequency of input.

Changing the Process

As mentioned earlier, the frequency-response curve in Figure 34-2-7 is unique to a particular system. When the process or any component in the process is changed, the frequency-response curve also will be changed. If a tank with a smaller diameter than the one in Figure 34-2-5 is employed with the same average flow rates, the Bode plot will be different. Figure 34-2-8 is a Bode plot of a process with a larger and smaller tank.

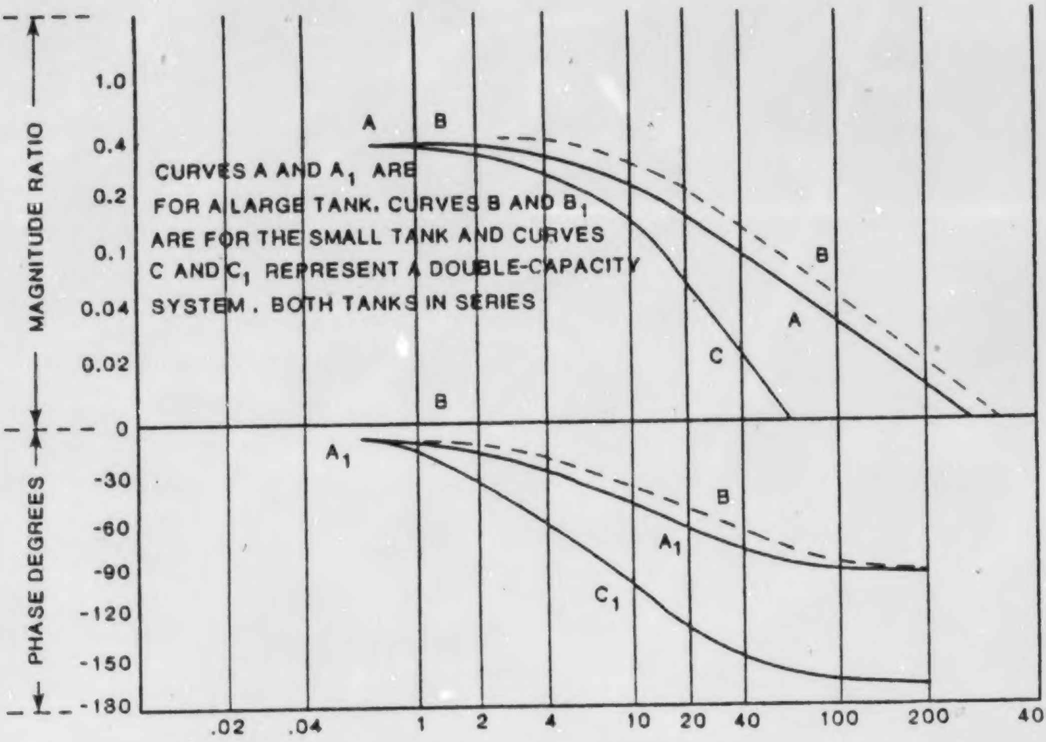


Figure 34-2-8. A Bode plot.

In many applications, the process is more complicated than the simple single-capacity level process previously illustrated. If the two tanks in Figure 34-2-5 were placed in series, with the outflow of the smaller tank feeding into the larger tank, level measurement in the larger tank would result in a greater phase shift. Level in the two tanks would not rise and fall in phase at higher frequencies. The two levels also would be out of phase with the inflow. Curves C and C_1 in Figure 34-2-8 represent a double-capacity system.

Preparation of the Bode Plot

Values of magnitude ratio and phase shift corresponding to frequency of the change in input to a system are listed in Table 34-2-1. To obtain enough information for a frequency response over a wide range of frequencies, the lowest frequency that produces a variation above a steady-state value is used as the first response. Magnitude ratio and phase shift are recorded along with the frequency. Frequency then is doubled, and the corresponding magnitude ratio and phase shift are recorded. The procedure is repeated until the maximum frequency to which the process can respond has been reached or until the frequency range of interest has been covered. When this has been obtained and compiled, the Bode plot is constructed.

TABLE 34-2-1. MAGNITUDE RATIO AND PHASE SHIFT FOR AN OPEN-LOOP LEVEL PROCESS AT NINE DIFFERENT FREQUENCIES.

Frequency Cycles per Minute (cpm)	Magnitude Ratio	Phase Shift Degrees
0.6	1.0	- 8
1.24	1.0	-10
2.4	0.895	-24.5
4.8	0.715	-37
9.6	0.51	-60
19.2	0.26	-75
38.4	0.135	-82
76.2	0.07	-85
152.4	0.035	-87

To combine responses of several components over a wide range of frequencies, the frequency and gain values are plotted on logarithmic scales. A linear scale is used to plot the difference. To make comparison of the gain and phase shift-plots easier, the same frequency scale is utilized. Also, to make the plot more convenient, the gain ratio can be converted to decibels, and the decibel value then can be plotted on a linear scale. This is possible because the decibel unit is a logarithmic ratio, as expressed in Equation 34-2-2.

$$\text{decibels (db)} = 20 \log_{10} G \qquad \text{Eq. 34-2-2}$$

where:

$G = \text{ratio of } \dfrac{\text{output amplitude}}{\text{input amplitude}}.$

The Bode plot in Figure 34-2-8 represents the frequency response for a level process with a large tank (curves A and A_1) and a level process with a smaller tank (curves B and B_1). The curves are identical except for their relative positions. The plot of magnitude ratio versus frequency for the smaller tank is shifted to the right and starts at the arrow located at B, extending to the point, as indicated by the dotted line at the extreme right end of the curve. Similarly, the plot of phase shift-versus-frequency is shifted to the right by the same amount. The phase-shift curve for the smaller tank starts at the point marked B_1 and extends as shown by the dotted lines at the right.

Analytical Determination of Frequency Response

In some situations, determination of frequency response of a system by analytical methods may be desirable. Once a process has been designed, the dynamic properties should be known before construction to allow for design changes that can be accomplished much more easily and cheaply before construction takes place. A frequency response analysis can be performed from the transfer function determined during the design and planning stages of the development of a process. If a frequency response analysis predicts an unstable process, changes can be made in the design to correct for this situation.

The input-output relationship of a system is defined by a set of differential equations in the time domain. Use of Laplace transforms converts the differential equation to the frequency domain in which the gain and phase shift of a system or component can be solved by algebraic equations. The transfer function then is obtained by solving of algebraic equations.

Equation 34-2-3 is for the time-domain of a single-capacity process.

$$\tau \frac{dh}{dt} + h = m \qquad \text{Eq. 34-2-3}$$

This is the transfer function expressed by a differential equation. The transfer function in the domain is indicated by Equation 34-2-4.

$$\frac{H}{M} = \frac{1}{\tau S + 1} \qquad \text{Eq. 34-2-4}$$

where:

τ = time constant.
h = time-domain output signal.
H = frequency-domain output signal.
m = time-domain input signal.
M = frequency-domain input signal.
S = frequency parameter.

For the special application of frequency response analysis, the input signal is a sine wave with a frequency in radians of ω; and the frequency parameter S is equal to $j\omega$, where $j = \sqrt{-1}$.

$$S = j\omega \text{ when } m = A \sin(\omega t)$$

The frequency response of a component then is defined by its transfer function when S is replaced by $j\omega$. For each value of ω (the frequency component), the transfer can be reduced to a single complex number. The magnitude of this complex number is the gain component at the frequency ω. The angle of the complex number is the phase shift at the frequency ω.

Complex numbers can be represented by a point on a two-dimensional plane called the "complex plane." The x axis is termed the "real axis," and the y axis is the imaginary, or j, axis. The complex number can be represented in either the rectangular or the polar notation. In the rectangular notation, the point on the plane is located by the x and y coordinates. In the polar notation, the point is located by a vector quantity at an angle of rotation from the x axis.

The example in Figure 34-2-9 will illustrate the two methods of representing complex numbers. Conversion from rectangular to polar, and from polar to rectangular, notation can be accomplished by application of trigonometric functions as follows:

Polar to Rectangular Conversion	Rectangular to Polar Conversion
$C = \frac{a}{\text{Cos } \theta}$	$C = \sqrt{a^2 + b^2}$
$= \frac{b}{\text{Sine } \theta}$	$\theta = \arctan b/a$

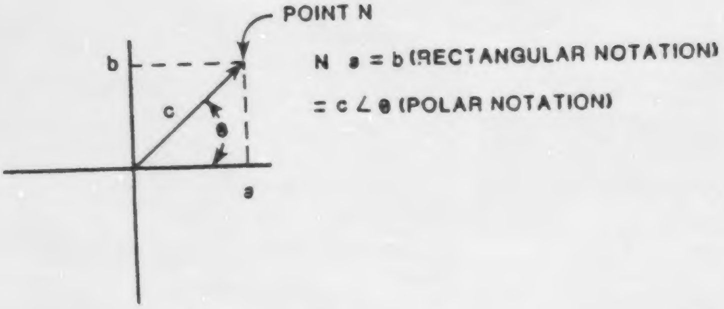


Figure 34-2-9. Complex number notation.

Frequency response of a component is determined by substitution of jω for S in the transfer function. When this substitution is made, the transfer function is a complex number converted to polar notation. The magnitude of the polar expression is the gain component at the frequency ω. The angle of the complex number is the phase shift of the component or system at the frequency ω.

EXAMPLE

Given: The first-order lag, defined by the equation $\frac{H}{M} = \frac{1}{\tau S + 1}$, has a time constant τ of 0.1 second. The frequency is 10 radians/second.

$\tau = 0.1$ second

$\omega = 10$ radians/sec.

Find: The frequency response.

Solution: Replace S in the above equation with j10, and replace τ with 0.1:

$$\frac{H}{M} = \frac{1}{\tau S + 1} = \frac{1}{0.1\ (j10) + 1} = \frac{1}{j + 1}$$

The j + 1 term represents a triangle with two equal sides. The polar notation for this term is $\frac{1}{\sqrt{2} \quad \angle 45^\circ}$.

$$\frac{H}{M} = \frac{1}{\sqrt{2} \ \angle 45^\circ} = \frac{1}{\sqrt{2}} \quad \angle -45^\circ$$

$$\frac{H}{M} = 0.707 \quad \angle -45^\circ$$

Since H = the frequency-domain output signal, and M = the frequency domain input signal, the gain term for the frequency response is 0.707, and the phase shift is -45°.

Answer: gain = 0.707.
phase shift = $\angle -45^\circ$.

This is the frequency response at a frequency of ω.

To complete a frequency-response analysis with the analytical method, the gain and phase shift corresponding to several different frequencies would be determined. A Bode plot would be constructed from the data obtained from the calculations.

THE COMBINED FREQUENCY RESPONSE OF SEVERAL COMPONENTS

When many components are connected together to form a complex system of components, the transfer function of the entire system can be determined by analysis of each component separately. This is necessary to determine frequency response of a system.

The components in Figure 34-2-10 are connected together to make a system. Transfer function and frequency response of the system are a function of the transfer function and frequency response of the individual components. If the frequency response of each component is known, the product of the individual gain components and the sum of the phase angles will give the frequency response of the system. The response of each component is given as a gain component at a phase angle, as shown. The total system gain is $(G_1) \times (G_2) \times (G_3) \times (G_4)$, and the phase angle is $\theta_1 + \theta_2 + \theta_3 + \theta_4$ or $G_T\theta_T = G_1G_2G_3G_4 \underline{|\,\theta_1 + \theta_2 + \theta_3 + \theta_4}$. This can also be expressed as:

$$\text{Total gain} = \left(\frac{\cancel{B}}{A}\right)\left(\frac{\cancel{C}}{\cancel{B}}\right)\left(\frac{\cancel{D}}{\cancel{C}}\right)\left(\frac{E}{\cancel{D}}\right) + \underline{|\,\theta_1 + \theta_2 + \theta_3 + \theta_4}$$

$$\text{Total gain} = \frac{E}{A} + \underline{|\,\theta_1 + \theta_2 + \theta_3 + \theta_4}$$

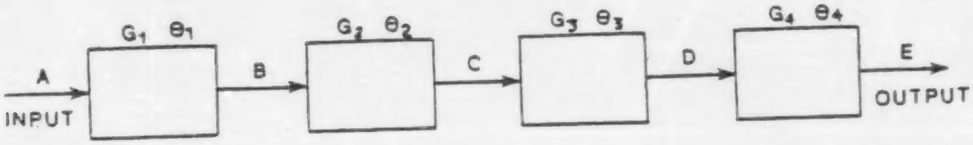


Figure 34-2-10. Four components connected in series.

EXAMPLE

Given: A temperature-process transfer function is $\frac{1}{7.8 \times 10^3 S + 1}$, and the transfer function of the temperature is $\frac{1}{36S + 1}$.

Find: The overall transfer function of the process and temperature transmitter.

Solution: The overall transfer function is the product of the individual transfer functions.

$$\left(\frac{1}{7.8 \times 10^3 S + 1}\right)\left(\frac{1}{36S + 1}\right) = \frac{1}{(7.8 \times 10^3 S + 1)(36S + 1)}$$

EXAMPLE

Given: The following component gain and phase shift were determined to be –

	Gain	Phase Shift
Valve	3.6	-2°
Process	2.4	-160°
Transmitter	0.9	-10°

Find: Total system transfer function.

Solution: Total gain is the product of the individual component gain.

$$G_T = G_1 \times G_2 \times G_3 = (3.6)(2.4)(0.9) = 7.77$$

$$\theta_T = (-2^\circ) + (-160^\circ) + (-10^\circ) = -172^\circ$$

The total frequency response is $7.77 \angle -172^\circ$.

APPLICATION OF FREQUENCY RESPONSE: PREDICTION OF PROCESS STABILITY

Stability is an important consideration in the design of a control system. Feedback control cannot be achieved if the process is not stable in open-loop control. Process stability can be predicted from a Bode plot of a process, which can be determined from the transfer characteristic used in frequency response analysis.

From an examination of a Bode plot, the process will be stable when two conditions are met:

- When the phase lag is less than 180° at the same frequency as unity gain, the system is stable.
- If the gain is less than unity at the same frequency for which the phase lag is 180°, the system is stable.

If the conditions for stability are not met, the components that determine phase shift and gain can be altered until stability is achieved. Conditions for process stability are met in the Bode plot in Figure 34-2-8.

By both experimental and analytical methods of the frequency-response analysis of process and component evaluation, other dynamic properties can be determined. Frequency-response curves for analysis of characteristics with given transfer functions (Table 34-2-2) can be constructed:

TABLE 34-2-2. CHARACTERISTICS AND CORRESPONDING TRANSFER FUNCTIONS.

Dynamic Property	Transfer Function
First-order lead component	$\frac{H}{M} = r S + 1$
Second-order lead component	$\frac{H}{M} = \frac{1}{\frac{1}{\omega^2} S + \frac{\alpha}{\omega^2} S + 1}$
Dead-time by component	$\frac{H}{M} = e^{-T_\sigma S}$
Integral component	$\frac{H}{M} = \frac{1}{AS}$

A frequency response of the above components is achieved in the same manner as those previously performed. The properties listed in Table 34-2-2 are for complex systems normally not encountered in simple feedback control applications. For further study of this subject, references are provided.

OPTIMIZING A CONTROL SYSTEM FOR FREQUENCY RESPONSE

Proportional Counter

Controller tuning techniques have been developed and debated for almost every control situation. Regardless of the method used to select the proper control mode settings, it generally is the ability of the controller to return a process to set point after a disturbance. Controller tuning by frequency response analysis probably will not improve a good control situation, although this may not be apparent when optimum control has been achieved. There is general agreement that the test for an optimum-tuned controller is reached when the process is returned to set point in four cycles of the process, with each successive cycle having an amplitude equal to one-fourth the preceding cycle. This is known as "quarter-amplitude damping." The controller gain that will produce quarter-amplitude damping in a closed-loop system is the reciprocal of the magnitude ratio plot of the Bode diagram at the frequency corresonding to the 150° phase shift. The frequency at this point is 40 cycles/min, which corresponds to magnitude ratio of 0.03 on curve C in Figure 34-2-8. The inverse of 0.03 is 33.33, which would be the controller gain for this example.

Derivative Control

Frequency response analysis can be employed to assist in the determination of the proper derivative time for optimum control. The derivative time is critical from the viewpoint of process stability. The gain at the -180° frequency point must be a safe distance below 1 (zero db), and the phase shift angle at zero-db frequency must be a safe distance above -180°. These margins are referred to as the "gain margin" and the "phase margin." These margins are normally about 5 db for the gain and 40° for the phase angle. Effects of the derivative control mode will change these margins by increasing the phase margin and decreasing gain margin. An optimum amount of derivative also will increase the maximum frequency limit.

The Bode plot can be used to predict the need for derivative control. When the ratio of $\frac{\omega - 270^\circ}{\omega - 180^\circ} > 5$, derivative is most useful, although a value of between 2 and 5 probably is also useful. When this value is less than two, derivative is not recommended.

Optimum derivative time setting can be derived from the Bode plot as follows:

1. Determine α from the desired increase in the phase margin (β_m) as mentioned above.

$$\alpha = \frac{1 - \sin \beta_m}{1 + \sin \beta_m}$$

2. Determine the derivative (T_d) from α and the open-loop zero-db frequency (ω_o db), which also is taken from the Bode plot.

$$\omega d = \sqrt{\alpha} \qquad \omega_o \text{ (0 db)}$$

$$T_d = \frac{1}{\omega_d}$$

Integral Control

Effects of the integral mode are to increase the low-frequency gain; to reduce the maximum frequency limit; and to reduce the phase margin. The integral control mode is most useful when the open-loop gain plot is level at the low-frequency end, but not useful when the open-loop gain graph slopes upward at the low-frequency end.

To determine the integral time setting (T_i) at, or about, the optimum amount to produce a phase angle of 10° at the open loop -170° frequency (ω -170°), calculate as follows:

$$\omega_i = 0.2 \ \omega \ -170^\circ$$

$$T_i = \frac{1}{\omega_i}$$

SUMMARY

A process or system can be analyzed by frequency response analysis to determine its dynamic characteristics, and from these characteristics process stability can be predicted. Also, from frequency response analysis, optimum control by the proper setting of the control modes can be achieved.

EXERCISES

1. Draw a feedback control system for the control of a tank level. List and explain the following components:
   a. Final control element.
   b. Primary element.
   c. Summer.
   d. Controller.
   e. Process.
2. Explain the method used to obtain data experimentally and that can be employed in frequency response analysis.
3. Given: The rectangular notation for a transfer function is $2j + 5$.
   Find: Gain and phase angle of the transfer function.
4. Given: Individual component gains and phase shifts are:
   $1.6 \; \underline{\big| -22^\circ} \qquad 2.2 \; \underline{\big| -54^\circ} \qquad 4.0 \; \underline{\big| -10^\circ}$
   Find: Total system gain and phase shift.

- 1 pump, 3/8" with 1/2-hp, 12-V d.c. motor. Jacquzy 3RM2B1.
- 1 control valve, 3/4" body pneumatic operated 3-15 psi. Fisher 512 RG. Air to open.
- 1 electronic d/p cell for level measurement, 4-20 mA output with adjustable input range 0-200 inches of water. Rosemont Model 1HP4E22.
- 1 current-to-pneumatic transducer, 4-20 mA input, 3-15 psi output. Fisher type 543.
- 1 electric two-pen strip chart recorder with slow and fast chart drive (approximately 1 in/hr and 1 in/min).
- 1 variable-frequency sine-wave generator capable of 20-mA output into 600-Ω load. Frequency range 0 to 1 mHz. Heath Schlumberger Model EU81A.
- 2 PVC pipes 6 ft x 12 in, capped at one end, with appropriate pipe connections for instruments and process piping.
  - Assorted pipe and pipe fittings necessary to connect the pump and instruments to the PVC pipe used for the process.
  - Assorted wire and tubing, with fittings necessary to connect the instruments.
  - 20-psi regulated air supply.
  - Voltage source for pump and instruments.
- 1 55-gal drum cut in half to be used for the overflow tank.
  - Water supply source to fill the tank.
  - Manufacturers' instruction manuals for all equipment.

PROCEDURES

1. Connect equipment to construct the liquid-level process illustrated in Figure 34-2-5.
2. Fill head tank and overflow tank with water.
3. Open air supply to I/P transducer; supply power to electronic level transmitter and strip chart recorder.
4. With generator on lowest frequency setting, a steady-state level, increase output to open the valve. Regulate the valve for about 50% level in the level tank as indicated on the strip chart recorder.
5. Slowly increase frequency of the generator until oscillations are detected on both pens of the recorder.
6. Obtain the frequency from the dial setting on the generator. Enter this frequency in Data Table 34-2-1.
7. Measure the phase shift between the two signals on the two-pen recorder; record this value.
8. Determine and record the ratio of the magnitude of the two signals on the recorder.
9. Double frequency; repeat Steps 6, 7, and 8.
10. Repeat Step 9, for a total of nine entries into Data Table 34-2-1.
11. This completes the experimental portion of this procedure. Secure all equipment.
12. From data in Data Table 34-2-1, construct a Bode plot similar to the one in Figure 34-2-8.
13. From the Bode plot, determine the following:
    a. Is the process stable?
    b. Optimum proportional band setting to provide closed-loop control.
    c. Is integral control necessary?
    d. What is the optimum integral value?
    e. Is derivative control necessary?
    f. What is the optimum derivative value?

DATA TABLE 34-2-1

	Frequency	Magnitude Ratio	Phase Shift
1			
2			
3			
4			
5			
6			
7			
8			
9			

REFERENCE MATERIALS

Bateson, Robert. Introduction to Control System Technology. Columbus, OH: Charles E. Merrill Publishing Company, 1973.

Instrument Society of America. Principles of Frequency Response (text of the ISA film of the same name). Research Triangle Park, NC: Instrument Society of America, 1958.

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Zoss, Leslie M. Applied Instrumentation in the Process Industries. Volume IV: Control Systems: Theory, Troubleshooting and Design. Houston, TX: Gulf Publishing Company, 1979.

TEST

1. Define the following terms:
   a. Frequency response analysis.

   b. System gain ratio.

   c. System phase shift.

   d. Bode plot.

2. List and explain two methods by which frequency analysis is performed.

3. List an advantage and a disadvantage of the methods in the answer to Test item 2.

4. Explain the principles of process design by frequency analysis for simple- and multi-component processes.

5. What is a Bode plot?

6. Discuss the principles of controller design by frequency analysis.

7. Given: The frequency domain equation for the first-order lag component is –

$$\frac{H}{M} = \frac{1}{\tau S + 1}$$

The time constant is 0.5 second.

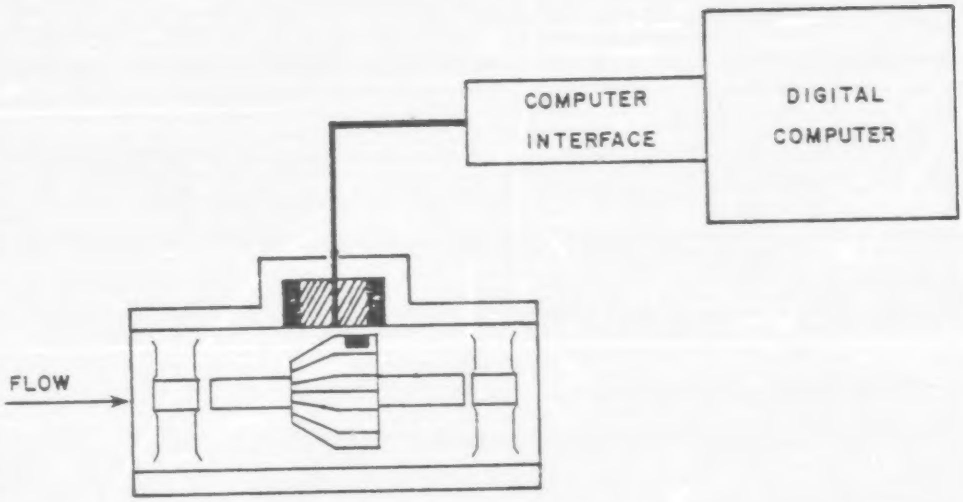
The frequency of the input is 5 radians/sec.

Find: The frequency response.

NUCLEAR TECHNOLOGY

MODULE 34-3

COMBINATION CONTROL SYSTEMS


COMPUTER INTERFACE
DIGITAL COMPUTER
FLOW

CONTROL SYSTEMS II
COURSE 34

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COURSE MODULES

CONTENTS

COURSE 34 CONTROL SYSTEMS II

MODULE 34-1 Introduction to Transfer Functions
MODULE 34-2 Frequency Response Analysis
⇨ MODULE 34-3 Combination Control Systems
MODULE 34-4 Controller Tuning
MODULE 34-5 Operational Amplifiers
MODULE 34-6 Microprocessor Utilization
MODULE 34-7 Microprocessor Programming

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INTRODUCTION

Many improvements and refinements of simple single variable-feedback control loops have been made to increase the control quality of processes in both nuclear and conventional installations. These innovations have resulted in process control optimization demanded by competitive manufacturing principles, environmental protection procedures, and resource conservation.

The purpose of this module is to present control schemes that, when utilized and applied properly, will enhance control quality. Cascade control, ratio control, adaptive control, and feedforward control will be covered. The selection and application of these control methods to improve control quality will be discussed.

MODULE PREREQUISITES

The student should have completed Course 3, "Principles of Process Instrumentation"; Course 6, "Instrumentation and Control of Reactors and Plant Systems"; Course 33, "Control Systems I"; and the previous module of this Course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
    Wild flow.

Controlled flow.
Primary control loop.
Secondary control loop.
Master controller.
Slave controller.
Control quality.

2. Explain the following control types:
   Cascade.
   Ratio.
   Adaptive.
   Feedforward.
3. List an application that involves each of the types of control in Objective 2, and explain the purpose and operation of each.
4. Explain the means by which control quality is improved by the control methods listed in Objective 2.

The purpose and justification of any control loop or control system is to maintain a dynamic process variable at an exact predetermined condition. A control loop is needed because the variable under control is dynamic; that is, it changes from the influence of other process variations and, therefore, needs regulation.

CONTROL QUALITY

The true test of any control system is the ability of that system to maintain the process variable at the desired condition. This condition is defined as the "process set point." From a review of feedback control principles, it should be realized that a controller cannot achieve this purpose exactly because the variable under control must change before corrective action can be generated by the control element to oppose the change. From the standpoint of quality, then, perfect control is impossible because of the inevitable deviations of process variables from optimum values. A measure of process control quality must concern the deviations between actual values and desired values during times of changes in disturbance variables affecting the process. The significance of this lies in the fact that a control system can be justified only to correct for disturbance variables. Without disturbance variables, control can be achieved by open-loop operation.

In the interest of control quality, it must be assumed that conditions that require control action will arise. When control action is required, control quality is measured in terms of the control system's ability to return the process to set point after a disturbance with minimum deviation and minimum duration.

MINIMUM DEVIATION

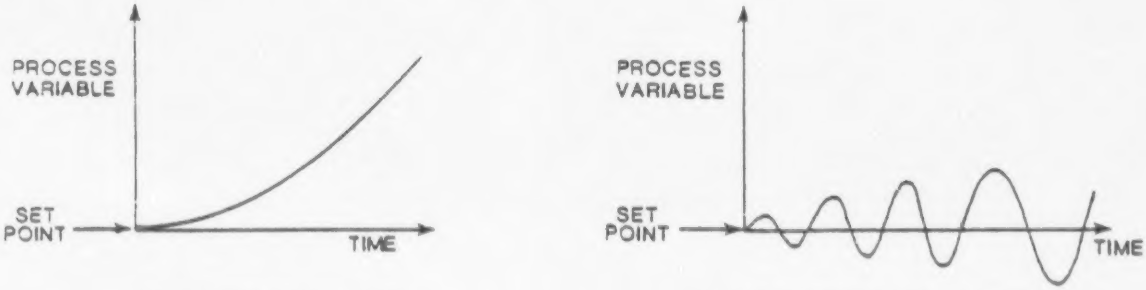
When a process control loop has been adjusted to control a dynamic variable at set point, a definition of control quality is "the extent to which a disturbance variable causes a deviation from set point." If the disturbance is a change in set point, control quality then is measured in terms of overshoot or undershoot of the dynamic variable with respect to reaching the new set point value. The deviation of process variable from set point during times of process or set-point disturbances should be minimized. This control criterion is known as "minimum deviation."

MINIMUM DURATION

If a disturbance does occur, some deviation will result because of the nature of the feedback control systems. The length of time before the dynamic variable reaches or adopts a new set point following a disturbance is another measure of control quality. This measure is "minimum duration."

STABILITY

A means of stable regulation of a dynamic process variable must be provided. "Stable regulation" means that the dynamic variable does not grow without limit or execute growing oscillations. Uncontrolled growth without limit and oscillation growth without limit are represented in Figure 34-3-1. Either condition in Figure 34-3-1 is unacceptable for stable process control. The quality of a process control loop is defined as through an evaluation of process stability, minimum deviation, and minimum duration.



(a) Growth without limit

(b) Oscillation growth without limit

Figure 34-3-1. Process response curves.

The condition depicted in Figure 34-3-2 is a process regulated by a control system that returns a process to set point with minimum deviation and minimum duration following a disturbance variable. This condition is known as "quarter-amplitude damping" because the amplitude of each succeeding cycle is one-quarter that of the preceding cycle. After four cycles, the process has been returned

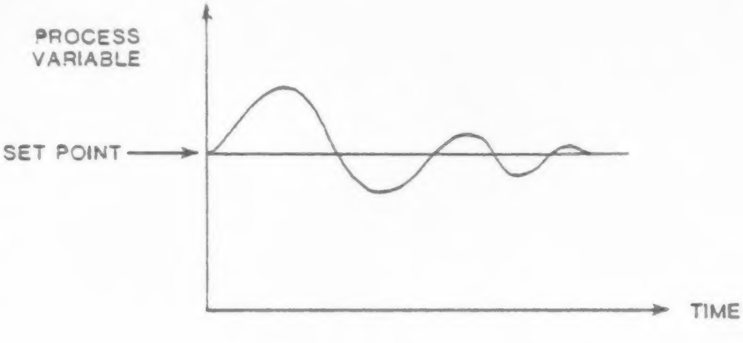


Figure 34-3-2. A process returning to set point with minimum deviation and minimum duration.

to set point. The extent to which quarter-amplitude damping is achieved defines the quality of control.

CASCADE CONTROL

Regardless of the variable to be controlled, flow usually is the manipulated variable. Both the processes in Figures 34-3-3 and 34-3-4 are controlled by change of a flow quantity in the process. By conventional feedback control means, a variation in level in Figure 34-3-3 will result in a change in the amount of flow into the tank. The level quantity is a function of the flow (the manipulated variable) into the tank. Remember that flow is not a controlled variable. Any controlled variable for feedback operation first must

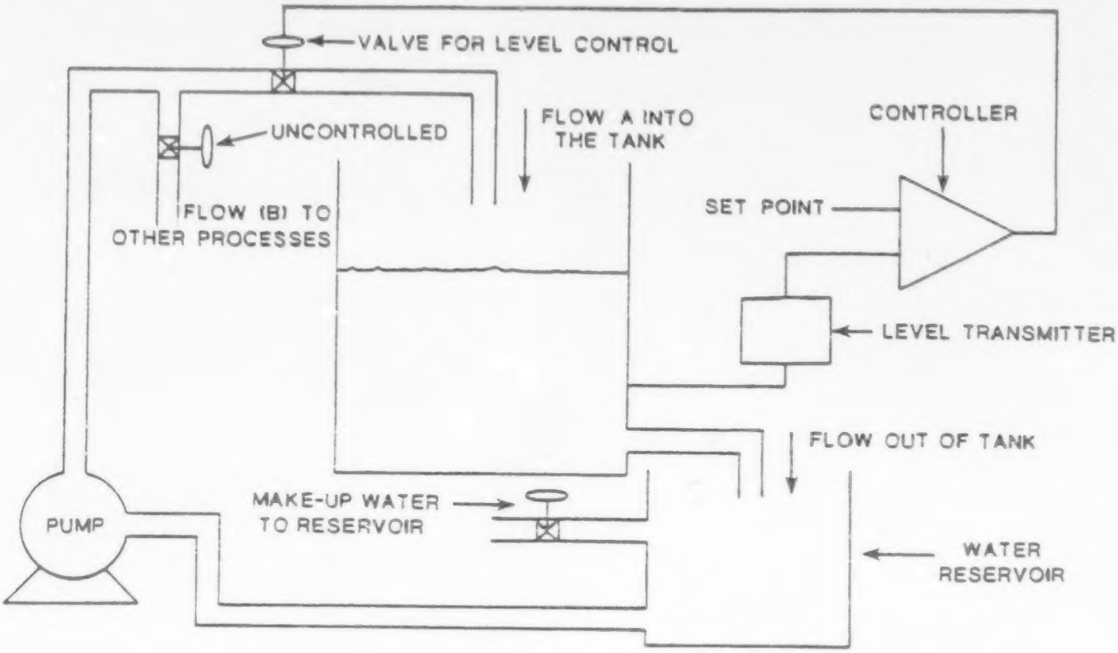

VALVE FOR LEVEL CONTROL
UNCONTROLLED
FLOW A INTO THE TANK
CONTROLLER
SET POINT
FLOW (B) TO OTHER PROCESSES
LEVEL TRANSMITTER
FLOW OUT OF TANK
MAKE-UP WATER TO RESERVOIR
PUMP
WATER RESERVOIR

Figure 34-3-3. A single-element level control loop.

be measured. Flow is not measured in the level process of Figure 34-3-3. If a change in flow B (an uncontrolled flow) resulted in a reduction of the pressure in the line upstream of the level control valve, the flow through the valve would decrease. This reduction in water flow into the tank would result in a reduction in level. The level controller, responding to the change in level, then would increase the flow. The dead time in most level processes is not very long; consequently, the time duration between the initial flow reduction caused by the decrease in pressure upstream of the valve and the resulting decrease in level normally is not great enough to cause a major level

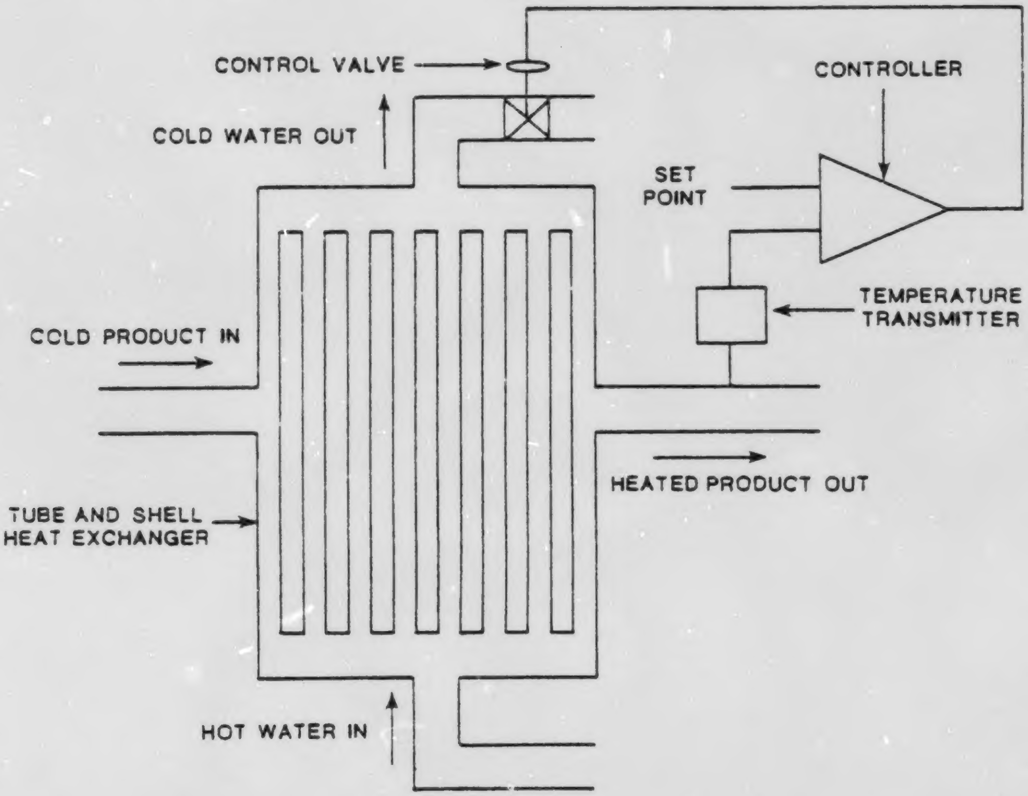

CONTROL VALVE
CONTROLLER
COLD WATER OUT
SET POINT
TEMPERATURE TRANSMITTER
COLD PRODUCT IN
HEATED PRODUCT OUT
TUBE AND SHELL HEAT EXCHANGER
HOT WATER IN

Figure 34-3-4. A single-element temperature process.

overshoot and undershoot. However, the temperature process in Figure 34-3-4 is a different matter.

An uncontrolled surge in the pressure that results in a decrease in water flow into the heat exchanger will cause a decrease in the temperature of the tubes. The product temperature then will decrease but, before the controller can cause the flow of water through the exchanger to increase, the reduction in temperature must be measured by the transmitter, which results in another amount of time lost in the process. When the controller finally does reposition the control valve, the temperature of the product leaving the exchanger may be at another value. In double-capacity processes such as that depicted in Figure 34-3-4, there is a considerable amount of phase shift between the input and the output of the process. Heat energy must be transferred from water (the manipulated variable that circulates through the tubes of the heat exchanger) to the tubes of the heat exchanger. Once this transfer has taken place, heat energy must be transferred to the product. When temperature of the product has changed, another energy transfer must occur between the product and the sensing element of transmitter.

Although the time lost in process measurement normally is not as great as for a change in temperature of the process, the response time of transmitters is significant. This is especially true for temperature transmitters. A protective shield around the transducer of the temperature transmitter which normally is used also increases the transmitter response time. Cascade control systems are used to improve the control quality of temperature and other processes with long lag time.

The temperature control system is represented in the block diagram in Figure 34-3-5. The system in Figure 34-3-6 consists of two control loops, a temperature-control loop and a flow-control loop.

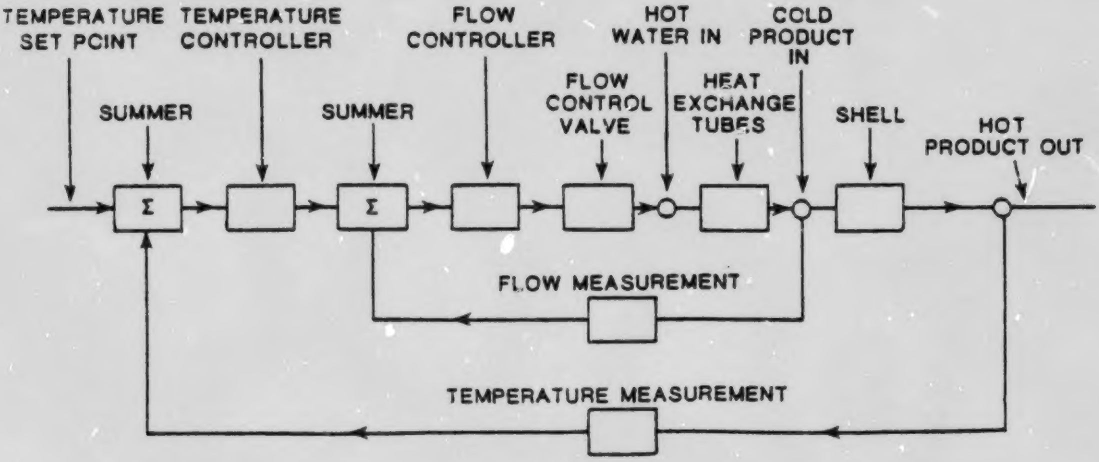

TEMPERATURE SET POINT
TEMPERATURE CONTROLLER
FLOW CONTROLLER
HOT WATER IN
COLD PRODUCT IN
SUMMER
SUMMER
FLOW CONTROL VALVE
HEAT EXCHANGE TUBES
SHELL
HOT PRODUCT OUT
Σ
Σ
FLOW MEASUREMENT
TEMPERATURE MEASUREMENT

Figure 34-3-5. Block diagram of a cascade temperature-control system.

The input to the cascade control system is the temperature set point to the temperature controller. The temperature controller is called the "master," or "primary," controller, whose output provides the set point for a flow controller, which is the "slave," or "secondary," controller. The flow controller regulates an amount of hot water (energy) into the system. Water temperature is controlled by the master, or temperature, controller. The two loops in the cascade system in Figure 34-3-5 also are known as the "outer loop" (temperature) and the "inner loop" (flow).

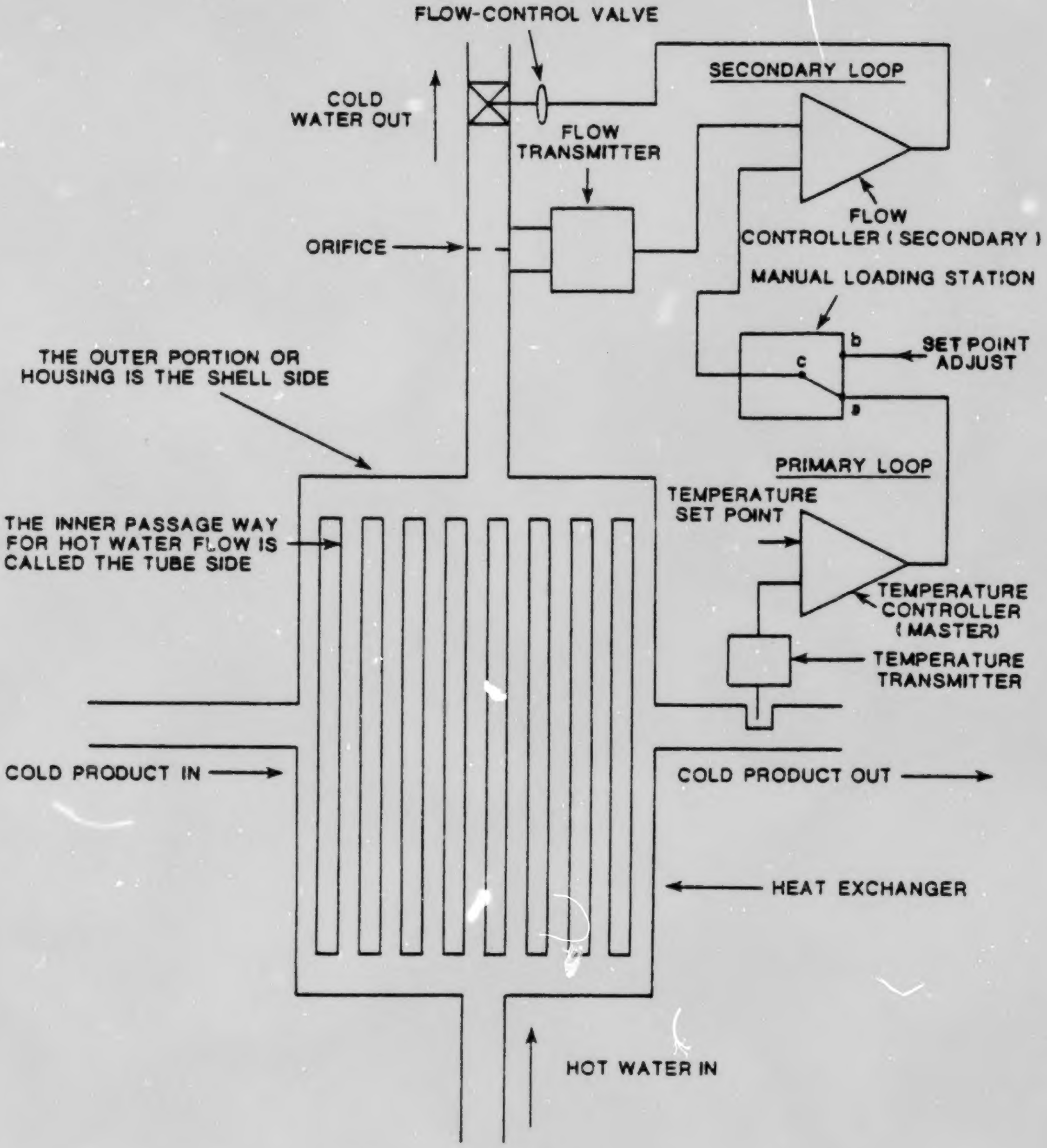
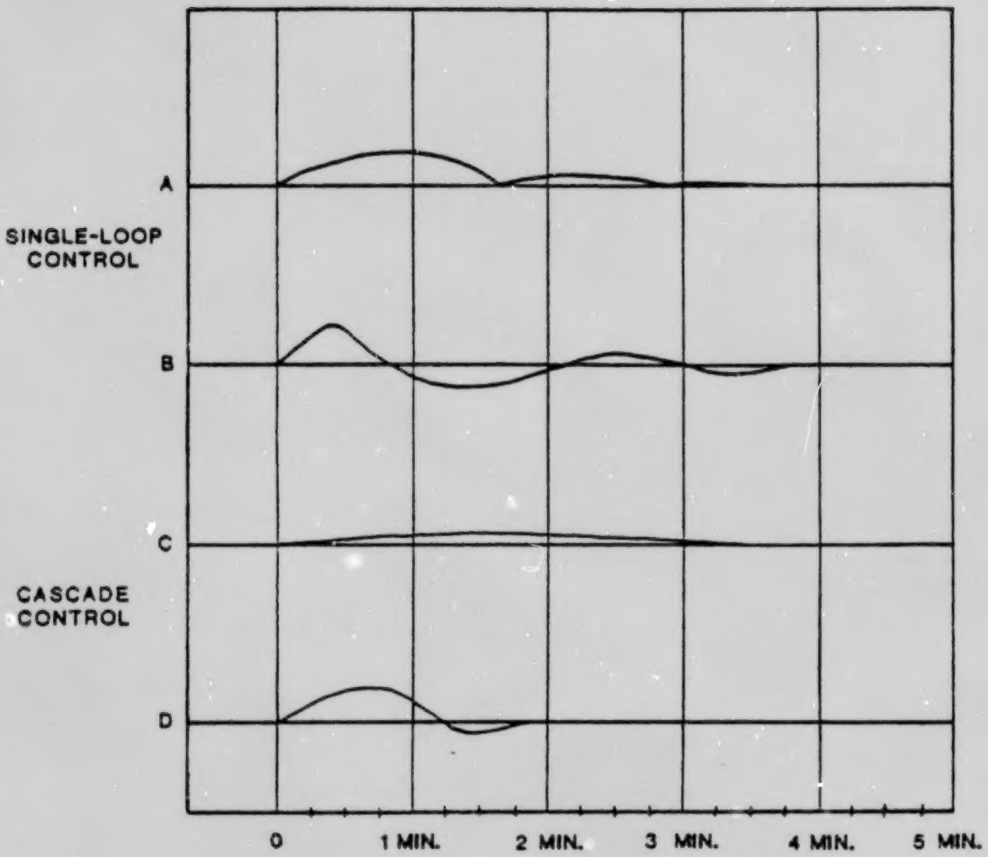

FLOW-CONTROL VALVE
SECONDARY LOOP
COLD WATER OUT
FLOW TRANSMITTER
FLOW CONTROLLER (SECONDARY)
ORIFICE
MANUAL LOADING STATION
b
c
a
SET POINT ADJUST
THE OUTER PORTION OR HOUSING IS THE SHELL SIDE
PRIMARY LOOP
TEMPERATURE SET POINT
THE INNER PASSAGE WAY FOR HOT WATER FLOW IS CALLED THE TUBE SIDE
TEMPERATURE CONTROLLER (MASTER)
TEMPERATURE TRANSMITTER
COLD PRODUCT IN
COLD PRODUCT OUT
HEAT EXCHANGER
HOT WATER IN

Figure 34-3-6. A cascade temperature-control system operated with a tube-and-shell heat exchanger.

The primary function of the secondary, or inner, loop is to isolate the control of hot water flow into the heat exchanger from the remainder of the system. This is accomplished by quick correction for any changes in the controlled variable (hot-water flow) of the secondary loop and reduction of the influence of these changes on the primary loop. The advantage of the cascade control system is the reduction of the response time of the entire process by the increased response time of the secondary loop. When an uncontrolled variable causes a change in the flow of hot water into the heat exchanger, the flow change is detected by the flow transmitter in the secondary loop. The flow transmitter creates an error signal on the input of the secondary controller, which generates an output to reposition the flow control valve to maintain the flow quantity of hot water into the heat exchanger. The control quality of the cascade system is greatly increased above that of a single-loop control system because the secondary control loop corrects for flow disturbances before they can affect the primary controlled variable (temperature).

Control improvements by use of cascade techniques depend upon the ratio of major time constants in the primary and secondary loops. The resultant improvements are greater as the ratio increases but can be significiant, even as the ratio approaches unity. The control system in Figure 34-3-4 should be compared with that of Figure 34-3-6. From an analysis of the temperature response with respect to an uncontrolled disturbance in the flow of hot water, it is evident that the cascade system with the independent flow controller can correct for these flow variations and, therefore, can provide a high quality of temperature control. Efficiency of the cascade system is shown graphically in Figure 34-3-7.



A. Temperature change caused by change in water flow – single loop.

B. Temperature change caused by process load change – single loop.

C. Temperature change caused by change in water flow – cascade.

D. Temperature change caused by process load change.

Figure 34-3-7. Control response to load changes.

As can be seen from curves A and C in Figure 34-3-7, a change in water flow into the heat exchanger causes a significant change in the temperature of the product. In the example shown, a stable condition does not reoccur until about four minutes have elapsed. The water-flow variation has little effect upon the product temperature when cascade control is employed. The upset in product temperature and the recovery time that results from a process load change are also less significant for the cascade system than for the single-loop systems represented by curves B and D in Figure 34-3-7.

STARTUP AND ADJUSTMENT OF A CASCADE SYSTEM

The instruments through which cascade control is implemented are illustrated in Figure 34-3-6. The flow loop is shown as the secondary, and the temperature loop as the primary. A manual loading station generates a set-point signal for the secondary controller in order that the loop can be "decoupled" for startup and troubleshooting procedures. Open-loop control of either or both of the loops also can be provided.

As with any control system, the process unit normally is brought up to operating conditions on open-loop control. This is because of the nonlinear characteristics of processes. These characteristics cause automatic control at several, or at various, operating points to be difficult, as, for example, during times of startup. Once the process has been brought up to operating condition on "hand" control, the secondary controller should be placed in the automatic mode of control. This procedure should be accomplished with the manual loading station, which provides the set point for the secondary controller. To avoid undue process instability, "bumpless" transfer procedures should be followed as outlined in the instruction manual for the particular controller. With the manual loading station switched for external set-point adjustment for the secondary controller as in Figure 34-3-6, points a and c would be open; and the primary controller output would be open ended. The primary controller should always be in the manual mode of operation for this situation to avoid a reset windup condition. With the secondary controller on automatic, it can be tuned to control the process.

Once the secondary controller has been tuned for optimum control of the flow process, the primary and secondary controllers can be coupled together by making points a and c common in the manual loading station. Once this has been done, the primary controller can be placed in the automatic mode of operation and tuned for optimum control of the overall system. Both controllers should be proportional plus reset. Very little reset will be needed for the primary controller, however, because it probably will be operated at a high value of gain.

CASCADE CONTROL APPLICATIONS

Use of cascade control loops can result in high control quality, although they require a second transmitter and controller, which increases the initial equipment cost and the maintenance and complexity of controller adjustments. Before cascade control is adapted to a process, the following conditions should exist:

- Load changes should be present and of appreciable magnitude.
- The secondary loop should be considerably faster than the primary loop.
- The ratio of the primary-loop time constant to the secondary-loop time constant should be greater than one.

The principal advantages of cascade control are –

- Variations and disturbances in the secondary loop are corrected by the secondary controller before they can influence the primary variable.
- Phase lag in the secondary portion of the process is reduced by the secondary loop, increasing the response time of the primary loop.
- The primary controller is able, with the secondary loop, to perform an exact manipulation of the mass or energy flow entering the process. Therefore, a better balance between supply and demand is achieved.

RATIO CONTROL

In a ratio control system, the two controlled variables establish the ratio K of two measured variables A and B. Ratio control is accomplished by manipulation of one variable, although the other variable is "wild," or uncontrolled. A ratio control system can be set up to compute A/B as a function of K in such a manner that K = A/B. A block diagram of this arrangement is presented in Figure 34-3-8. In this system, the ratio of two variables is employed as the input to the controller. The divider is within the closed loop,

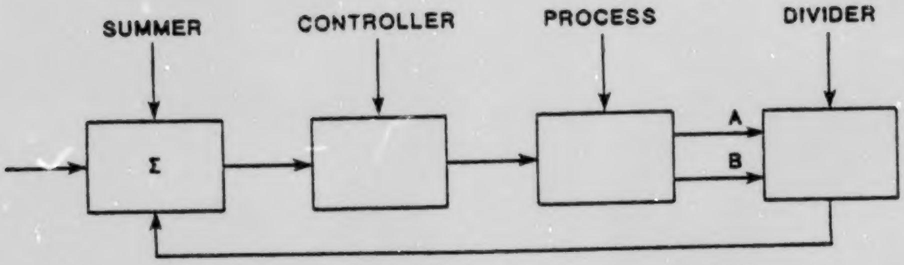

SUMMER
CONTROLLER
PROCESS
DIVIDER
Σ
A
B

Figure 34-3-8. A ratio control system.

regardless of which variable is affected by the controller output. If A is manipulated, the loop gain changes with the wild variable B. If B is manipulated, the loop is nonlinear because the gain changes with the controller output. Both situations are undesirable.

To overcome these problems, the ratio calculations are moved out of the closed loop and into the set-point circuit. The ratio then becomes R = KB when A is controlled and A/K when B is controlled. The method of set-point calculation is illustrated in Figure 34-3-9. In this configuration, one of the variables is controlled, and the other generates a set point. The wild variable is multipled by the adjustable coefficient K in the ratio station.

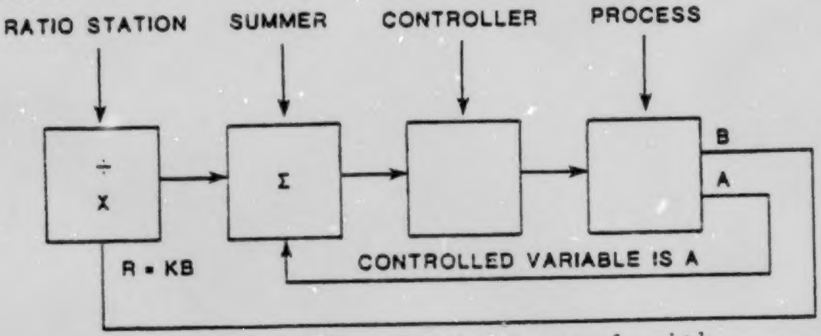

RATIO STATION
SUMMER
CONTROLLER
PROCESS
÷
X
Σ
B
A
R = KB
CONTROLLED VARIABLE IS A

Figure 34-3-9. Ratio control with calculations in the set point.

RATIO FLOW CONTROL

The most common application of flow control is a process in which flow quantities must be regulated in an exact proportion to another uncontrolled, or wild, flow (Figure 34-3-10). Any number of flow streams can be set in ratio to the wild flow. The objective of such a control system is to blend the flow rates of materials into a vessel to obtain a proper mix of the materials.

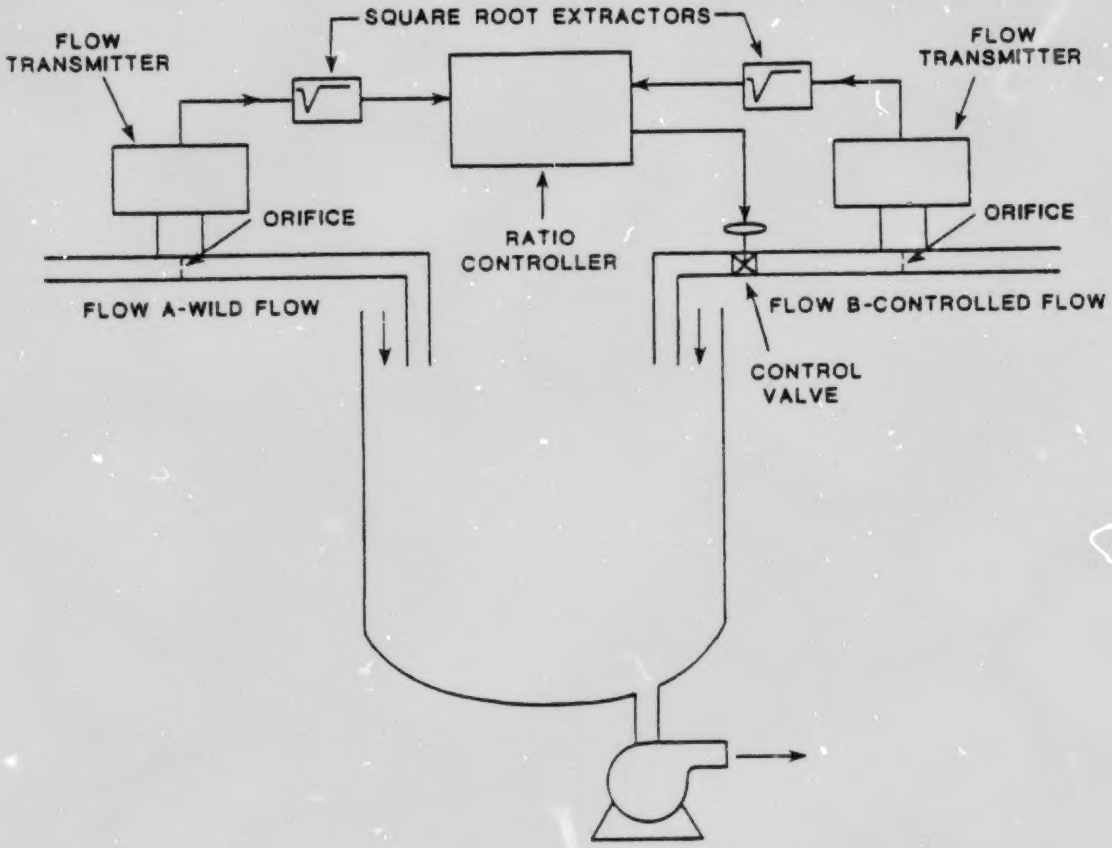

SQUARE ROOT EXTRACTORS
FLOW TRANSMITTER
FLOW TRANSMITTER
ORIFICE
RATIO CONTROLLER
ORIFICE
FLOW A-WILD FLOW
FLOW B-CONTROLLED FLOW
CONTROL VALVE

Figure 34-3-10. A flow ratio control system.

The ratio control system illustrated in Figure 34-3-10 controls flow B in an exact proportion to flow A. The ratio controller has two inputs — one from each of two flow transmitters. An output is generated in order to position the valve that regulates the controlled flow for the proper ratio. The square root extractors linearize the exponential signal from the flow transmitters. The input signals to the rate controller must be linear with respect to flow rates in order to maintain a constant flow ratio. When linear flow transmitters measure the flow, square root extractors are not required.

An actual ratio setting of as near 100% as possible usually is desirable in the design of ratio control loops. Actual ratio is calculated from Equation 34-3-1.

$$r_a = \frac{m_s}{m_p}(r_d)$$

Equation 34-3-1
(Equation = Eq.)

where:

r_a = actual ratio, in percent.
m_s = secondary meter span.
m_p = primary meter span.
r_d = ratio dial setting, in percent.

EXAMPLE

Given: In a particular flow system, there must be four times as much flow B as flow A. The ratio of flow B to flow A, therefore, is 4:1; and the span of the flow transmitter should be in the same ratio. The secondary meter span (flow A) is 25 gpm, and the primary meter span (flow B) is 100 gpm.

Find: The actual ratio.

Solution: Calculate from Equation 34-3-1:

$$r_a = \frac{m_s}{m_p} (r_d)$$

$$= \frac{25 \text{ gpm}}{100 \text{ gpm}} \quad (100\%)$$

$$r_a = 25\%.$$

A dial setting of 100% was on the ratio controller, and the actual ratio was selected from the span of the flow transmitters.

EXAMPLE

Given: A system in which the secondary meter span is 20 gpm and the primary meter span is 60 gpm.

Find: The actual ratio for a dial setting of 50% on the ratio controller.

Solution:

$$r_a = \frac{m_s}{m_p} (r_d)$$

$$= \frac{20 \text{ gpm}}{60 \text{ gpm}} (50\%)$$

$$r_a = 16.7\%.$$

EXAMPLE

Given: A system in which the secondary meter span is 10 gpm and the primary meter span is 30 gpm.

Find: The percent setting for a ratio of $\frac{\text{secondary}}{\text{primary}} = \frac{1}{4}$.

Solution: Again, use Equation 34-3-1, rearranging as required:

$$r_a = \frac{m_s}{m_p}(r_d)$$

$$\frac{1}{4} = \frac{10}{30}(r_d)$$

$$r_d = \frac{1}{4} \div \frac{10}{30}$$

$$\frac{1}{4} \cdot \frac{30}{10} = 0.75$$

$$r_d = 75\%.$$

To refer to the primary flow as "wild" can be misleading, although it sometimes is, as in Figure 34-3-10. In Figure 34-3-11, neither flow is wild; both are controlled. The primary flow in this case is controlled, and the secondary flow is controlled in proportion to the controlled primary flow.

For systems in which two flows are ratioed together, the foregoing discussion has assumed that the integral time setting is small and that the valve lag, which is also small, is most often the longest time constant in the loop. These assumptions are valid for most control loops that comprise the majority of all ratio control applications. In other types of ratio control systems, where the previous assumptions may not be valid, a dynamic analysis of the process may have to be completed to determine the ability of the secondary variable to follow the primary variable.

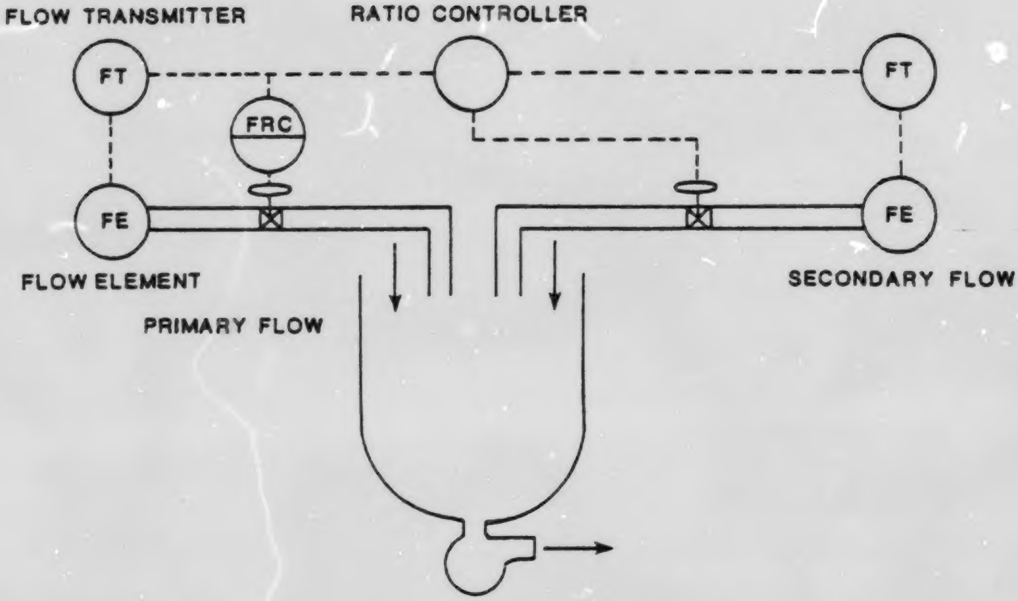

FLOW TRANSMITTER
RATIO CONTROLLER
FT
FRC
FT
FE
FE
FLOW ELEMENT
SECONDARY FLOW
PRIMARY FLOW

Figure 34-3-11. Flow ratio control system with controlled primary flow.

When the process time constants are not compatible, there will be an error in ratio. This will be true during startup and when major disturbances occur in the primary flow. Control of the primary flow, as was shown in Figure 34-3-11, will help to minimize the problems. Ratio control normally is considered a continuous process; and for such applications, error caused during startup usually can be neglected.

FEEDFORWARD CONTROL

Feedforward control applies to a system in which a balance between supply and demand is accomplished by measurement of both the demand potential and the demand load to obtain information used to regulate the supply.

The process to be controlled must be completely understood in order that equations that state the material balance and any required energy balance can be written. Any interactions between the material and energy balance also must be understood.

Once the equations are written, they are manipulated in such a manner that they can be solved by instrumentation components. Until recently, a drawback to the development of feedforward control techniques was the lack of equipment available for the mathematical computations necessary to solve the equations.

The principle of feedforward control may be easier to understand when applied to the effects of a cascade control system: Process variations that result from disturbances in hot water are eliminated by the secondary controller depicted in Figure 34-3-6. The result is observable in Figure 34-3-7. The effect of primary-loop variations and the resulting disturbance in the controlled variable is another matter. Cascade techniques do not improve the control quality enough to justify such applications.

Level processes are not good candidates for feedforward control applications because of the simplicity of such processes; however, an example will be used as an aid to understanding. The variables that affect the level in Figure 34-3-12 are the flow rates into, and out of, the tank. At high temperature variations, the level will change with temperature as the liquid expands and contracts. Although the variable may need to be considered in some applications, the effect of level changes with temperature variations will be neglected in this example.

The level can be expressed in terms of flow; Equation 34-3-2 states the material balance of the process. For a steady-state level condition, the flow into the tank must equal the flow out.

$$A + B + C = D + E \qquad \text{Eq. 34-3-2}$$

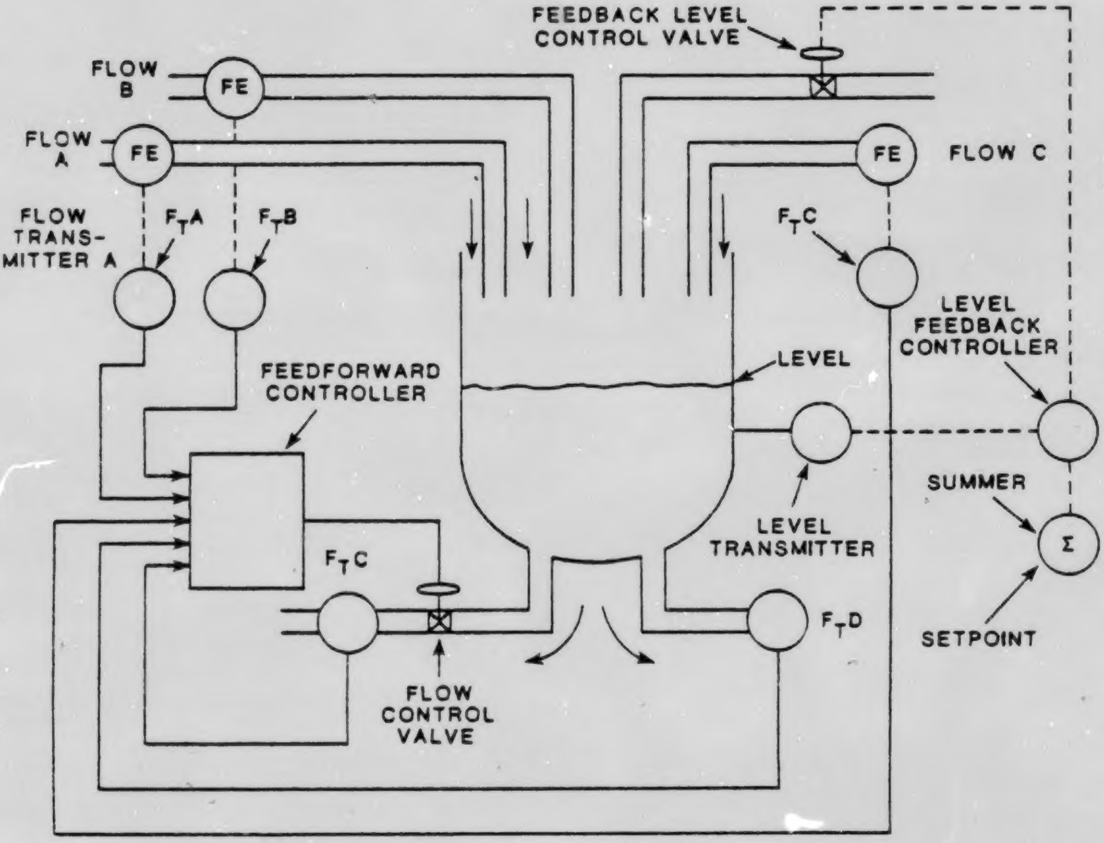

FEEDBACK LEVEL CONTROL VALVE
FLOW B
FE
FLOW A
FE
FE
FLOW C
FLOW TRANSMITTER A
F_TA
F_TB
F_TC
LEVEL
LEVEL FEEDBACK CONTROLLER
FEEDFORWARD CONTROLLER
SUMMER
Σ
LEVEL TRANSMITTER
F_TC
F_TD
SETPOINT
FLOW CONTROL VALVE

Figure 34-3-12. Feedforward control of a level process.

When the steady-state material balance equation is satisfied, the level will be maintained. But when any flow changes, one or more of the other flows must be changed in accordance with the equation to maintain the material balance. To accomplish this, the equation is solved for a flow selected to be the manipulated variable. This was flow rate C in Figure 34-3-11, and the feedforward controller solves the following expression:

$$C = (D + E) - (A + B) \qquad \text{Eq. 34-3-3}$$

When any of the flow rates on the right side of the equation change, the feedforward controller will cause flow C to change according to Equation 34-3-2 and, by so doing, will maintain a material balance (supply and demand) on the process.

Significantly, the controlled variable — level, in the previous example — is not one of the measured variables. Since this is a rigid requirement for feedback closed-loop control, the control is open loop. If any variable other than those in the feedforward equation causes the level to change, control will not be achieved. Feedback control is always used in conjunction with the feedforward control scheme to correct for variations not accounted for in the feedforward equation. Level variation caused by temperature change is an example of this. Feedback control can be provided by addition of a feedback loop and sizing of the control valve for about 10% of the total control, as illustrated in Figure 34-3-12.

The obvious question at this point concerning feedforward control is "Why?" Obviously, much more control hardware and many more engineering manhours are required for implementation. The answer is that the process (1) must be difficult or impossible to control by feedback means or (2) the quality of feedforward control must be an improvement over that of a feedback control, to the extent that feedforward control is justified. Neither case is true for the many processes in which feedback control is adequate.

ADAPTIVE CONTROL

As indicated in previous discussions, control theory usually is based upon linear control systems. In practice, however, flow control systems are linear. The system approaches linearity around a fixed central point and usually does not experience great load changes. This factor makes optimum control by feedback means possible because small variations on a nonlinear curve appear to be linear. Exceptions to this premise are process startup, batching operations, and control of pH. Startup and batching operations experience large load changes as well as variations in set point, and they normally are not to be considered as continuous control processes. The control of pH usually is a continuous process in nuclear installations and is difficult to control by conventional feedback applications because of the extreme nonlinear control characteristics (Figure 34-3-13). Feedforward control can be used successfully in many pH systems, but often difficulty is encountered in stating the exact operating conditions to the extent that the feedforward equation can be written. In such circumstances, adaptive control techniques have been employed. With this approach, controller adjustments are varied or adapted as a function of some process variable to add to control quality and to assist in maintaining stability in the process.

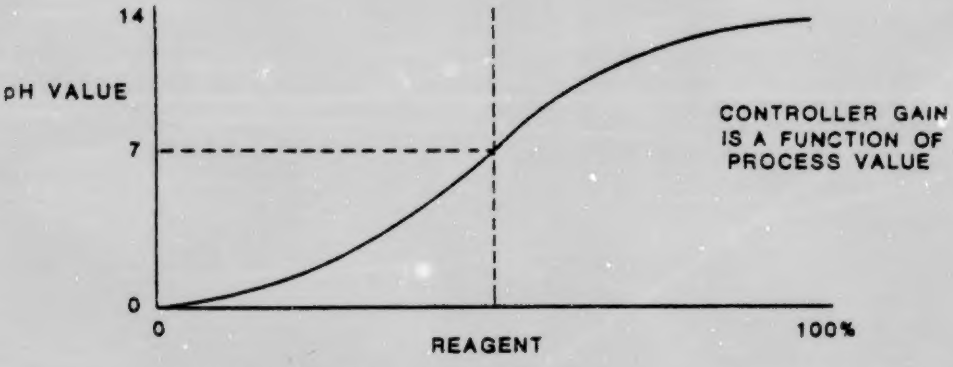


Figure 34-3-13. A nonlinear process using adaptive control.

Earlier adaptive control techniques employed the utilization of characterized valves. This method is based upon the use of control valves where gain changes are opposite to process gain changes. The curves in Figure 34-3-14 display the characteristic of flow measurement based on differential producers, orifice plates, etc., and the flow characteristics of an equal-percentage control valve. The combination of the two curves represents linearity. If the flow controller is assumed to be linear (the usual case), the valve characteristic is the reciprocal of the flow transmitter characteristic. The combination of the two opposing characteristics will produce a constant gain at any flow rate.

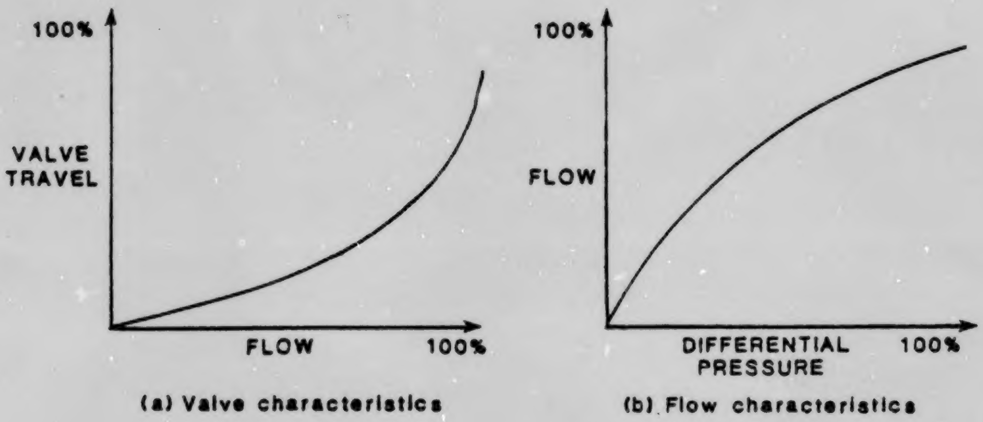


Figure 34-3-14. Nonlinear flow and valve characteristics.

The process characteristic curve in Figure 34-3-13 is for a pH process. This represents possibly the worst case of process nonlinearity encountered in nuclear installations. Control can be accomplished successfully for minor load changes around a specific control point; but for large variation in pH value, the process gain variations would change the total loop gain to the extent that the loop no longer would be tuned for optimum control. A solution to this situation is the use of an adaptive controller whose gain will change at different operating points on the pH titration curve. When the pH value is close to seven, a small amount of reagent will change the pH value significantly. This condition represents a high-gain process that requires a low-gain controller. When the pH value is on either extreme point of the curve, a large amount of reagent is required to cause a change in the pH value. This represents a low-gain process that requires a high-gain controller. The gain of an adaptive controller would be governed by the operating point on the pH curve.

EXERCISES

1. Given: a. The secondary meter span of a ratio control system is 40 gpm.
   b. The primary meter span is 80 gpm.
   Find: The actual flow ratio.
2. Given: a. The actual ratio of a ratio controller is 1/4 = 25%.
   b. The secondary meter span = 20 gpm.
   c. The primary meter span = 60 gpm.
   Find: The percent setting for the ratio controller.
3. Given: A level process has two input flows (A and B) and three ouput flows (C, D, and E).
   Find: a. The feedforward equation to state the material balance in the process.
   b. The equation to control level by manipulation of flow D.

MATERIALS

1 control valve with the following specifications: 1/2" body; pneumatic operated 3-15 psig. Fisher Type 512 RGS.

2 d/p cells with input range adjustable from 0-20 in H_2O to 0-200 in H_2O; output 3-15 psig. Foxboro Model 13-A.

1 controller with fast chart drive (1 in/min), pneumatic, with proportional plus reset plus derivative control mode. 3-15 psig input and output. Foxboro Model 120.

1 controller with fast chart drive (1 in/min), pneumatic, with proportional plus reset plus derivative control modes. 3-15 psig input and output. Equipped with 3-15 psig external set point adjust. Foxboro Model 120.

1 orifice meter with 1/2-in concentric orifice. Perry Equipment Corp., Type 1430.
1 pneumatic loading station, 3-15 psig input and output. Foxboro Model 57SRG2.
1 pump, 3/4" with 1/2-hp motor, 110 V a.c. Jacquzy Model 3RM25 1/A.
1 tank to be used for level process.
6 ft of 12" I.D. PVC pipe with end caps and appropriate fittings for process and instrument connections.
1 tank to be used as reservoir, approximately 50 gal capacity.
Manufacturer's instruction manuals for instruments and equipment.
Assorted piping, tubing and wiring for instrument and process connection.
2 1/2-in regulator valves, standard globe or needle valves.

PROCEDURES

PROCEDURE 1: LEVEL RESPONSE TO FLOW AND LOAD CHANGE FOR SINGLE-ELEMENT CONTROL

1. Follow the manufacturer's recommendations for installation procedures, and construct the cascade control system illustrated in Figure 34-3-15. For the first portion of this procedure, connect the output of the level controller to the flow control valve. The secondary (flow) control loop is now bypassed, and the process will be controlled by the level controller.

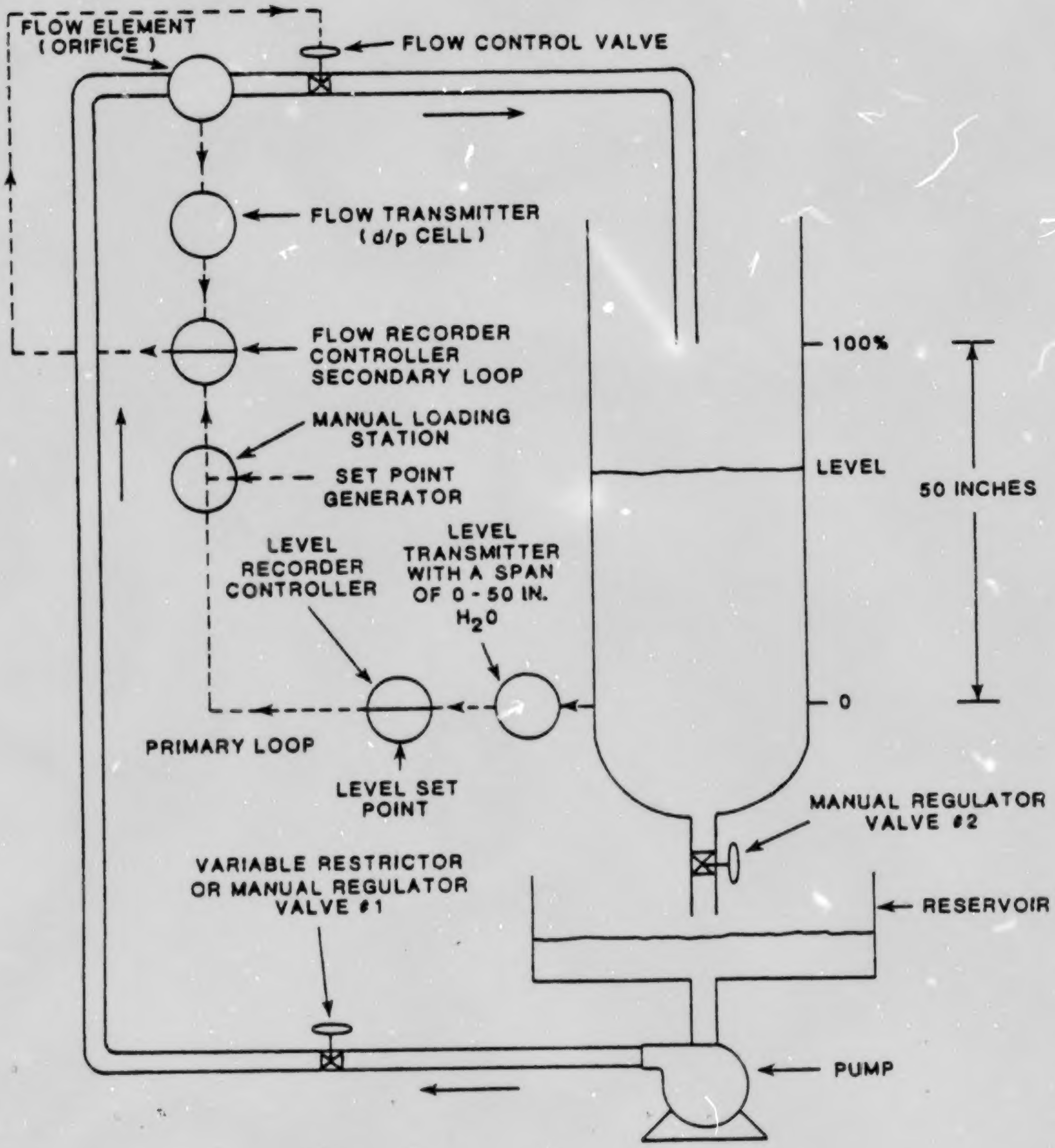

FLOW ELEMENT (ORIFICE)
FLOW CONTROL VALVE
FLOW TRANSMITTER (d/p CELL)
FLOW RECORDER CONTROLLER SECONDARY LOOP
MANUAL LOADING STATION
SET POINT GENERATOR
LEVEL RECORDER CONTROLLER
LEVEL TRANSMITTER WITH A SPAN OF 0 - 50 IN. H_2O
100%
LEVEL
50 INCHES
0
PRIMARY LOOP
LEVEL SET POINT
MANUAL REGULATOR VALVE #2
VARIABLE RESTRICTOR OR MANUAL REGULATOR VALVE #1
RESERVOIR
PUMP

Figure 34-3-15. Experimental setup for cascade control system.

2. Place the level controller into the manual mode of operation, and check the valve operation to determine if it opens or closes upon an increase in signal from the controller.
3. Set controller action to provide negative feedback in the control loop.
4. Fill reservoir with water; open regulator valves 1 and 2.
5. Open the control valve 50% with the level controller; start pump.
6. Adjust regulator valve No. 2 for a 50% level in the tank as indicated by the level recorder.
7. When the level has stabilized at 50%, place level controller into automatic mode of operations.
8. Tune level controller for optimum control. Tuning will be achieved when quarter-amplitude damping results.
9. Decrease flow into the tank by about 10% (as indicated by flow recorder) by closing regulator valve No. 1. For use in Procedure II, estimate and note the amount the valve was adjusted.
10. Note the response displayed on the chart of the level recorder; mark this as curve A. This is the level response to a flow change.
11. When the level has reached a new value and is stable, close regulator valve No. 2 until a noticeable amount of change in flow rate from the tank has been detected. Note the response displayed on the chart of the level recorder; mark this response as curve D. This is the level response to a load change on the level process.
12. Close the two regulator valves; stop pump.

PROCEDURE 2: LEVEL RESPONSE TO FLOW AND LOAD CHANGE FOR CASCADE CONTROL

1. Connect the primary and secondary loops for cascade operation by connecting the output of the level controller to the set point of the flow controller. Position the manual loading station in such a manner that the set point to the flow controller is from the set-point generator. The cascade loop is now decoupled, and the output of the flow controller is connected to the valve.
2. Place both the primary controller (level) and the secondary controller (flow) into the manual mode of operation.
3. Open regulator valve 1, and close regulator valve 2. With the flow controller, open the flow control valve 50%.
4. Start pump; adjust regulator valve 2 for 50% level in the tank as indicated by the level recorder.
5. With set-point generator in the manual loading station providing the set point for the flow controller, place the secondary controller into the automatic mode of operation.
6. Tune the secondary loop for optimum control or until quarter-amplitude damping results.
7. Place primary controller (level) into the automatic mode of operation; position switch on manual loading station such that the primary controller is provided the set point for the controller. The loop is now on cascade control.
8. Tune the primary controller for optimum control of the level process or until quarter-amplitude damping results.

9. When level is stable, close regulator valve No. 1 by the same amount as estimated in Step 9 of Procedure 1.
10. Note response displayed on the level recorder chart; mark this response as curve C. This is the response of the level process to a flow change for cascade control.
11. When the level has reached a new value and is stable, close regulator valve No. 2 until a noticeable amount of change in flow rate from the tank has been detected. Note the response exhibited on the chart of the level recorder; mark this response as curve D. This is the level response to a load change on the level process for cascade control.
12. Close regulator valves 1 and 2; stop pump.

DATA TABLES

None.

Curves A, B, C, and D marked on the level chart provide data for the procedures.

REFERENCE MATERIALS

Anderson, Norman A. Instrumentation for Process Measurement and Control. 2nd ed. Philadelphia, PA: Chilton Company, 1972.

Shinsky, F.G. Process Control Systems. New York: McGraw-Hill Book Company, 1967.

Zoss, Leslie M. Applied Instrumentation in the Process Industries. Volume IV: Control Systems: Theory, Troubleshooting and Design. Houston, TX: Gulf Publishing Company, 1979.

1. Compare response curves A with C and B with D, and answer the following questions:
   a. Which of the curves A or C represents a higher quality of control? Explain.

   b. Which of the curves B or D represents a higher quality of control? Explain.

   c. State the purpose and advantage of cascade control; justify answer with reference to the curves.

2. Define the following terms:
   a. Ratio control.

   b. Wild flow.

   c. Controlled flow.

   d. Primary control loop.

   e. Secondary control loop.

3. Explain the principles of feedforward control; compare this means of control to feedback control in terms of –
   a. Advantages.

b. Disadvantages.

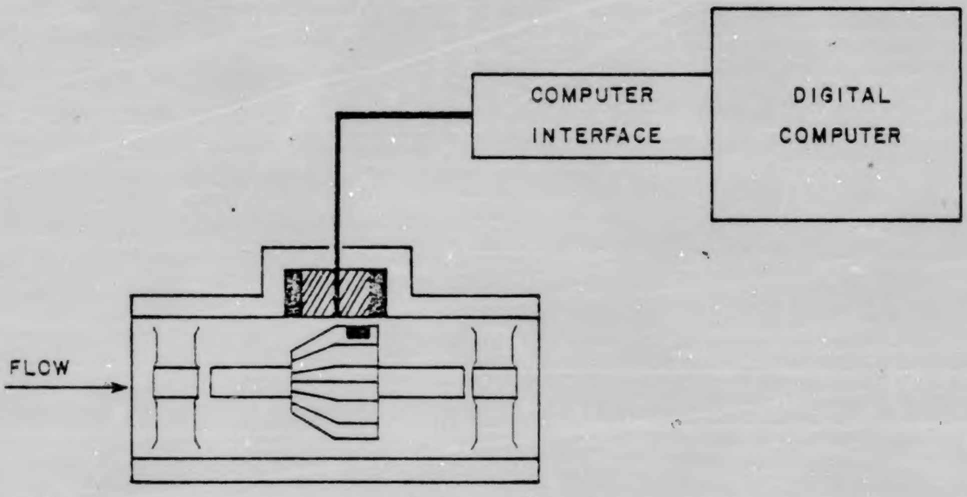
4. List a probable application of feedforward control.

5. Define adaptive control; list a possible application.

NUCLEAR TECHNC

MODULE 34 - 4

CONTROLLER TUNING


COMPUTER INTERFACE
DIGITAL COMPUTER
FLOW

CONTROL SYSTEMS II
COURSE 34

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

COURSE MODULES

CONTENTS

COURSE 34 CONTROL SYSTEMS II

MODULE 34-1	Introduction to Transfer Functions
MODULE 34-2	Frequency Response Analysis
MODULE 34-3	Combination Control Systems
⇨ MODULE 34-4	Controller Tuning
MODULE 34-5	Operational Amplifiers
MODULE 34-6	Microprocessor Utilization
MODULE 34-7	Microprocessor Programming

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INTRODUCTION

For any control system, the quality of process control is dependent upon proper selection and application of components in the control loop. Optimum process control can be achieved only when this objective is met. This alone, however, does not assure optimum control. Proper selection of the control mode settings is required to provide the exact match of loop components necessary to accomplish material and energy balances in the process system. The purpose of this module is to discuss parameters within the control system that determine control-mode settings and to present several means by which proper settings can be obtained.

MODULE PREREQUISITES

The student should have completed Course 3, "Principles of Process Instrumentation"; Course 6, "Instrumentation and Control of Reactors and Plant Systems"; Course 33, "Control Systems I"; and all previous modules of this Course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:

- Controller tuning.
- Process stability.
- Critical damping.
- Overdamped response.
- Underdamped response.
- Overshoot.
- Oscillation.

2. List the control-loop parameters that determine control-mode settings.
3. Explain the reason for controller tuning.
4. List and discuss three methods of controller tuning.
5. Give the advantages of optimum control.
6. Discuss a method used to check for optimum control.
7. Determine proper control-mode settings for controllers used on a process trainer.
8. Given the appropriate equations and data, determine control-mode settings for critical damping and for quarter-amplitude damping.

SUBJECT MATTER

The output of a control system is a representation of input: The input-output relationship is characterized by the transfer function, which describes the fundamental changes between the input and output of a system. These changes are a result of the magnitude and phase-shift displacement of the input and output (Figure 34-4-1). The magnitude displacement is expressed in terms of overall loop gain, and the phase shift angle is a representation of time lags (dead time plus lag time) in the system.

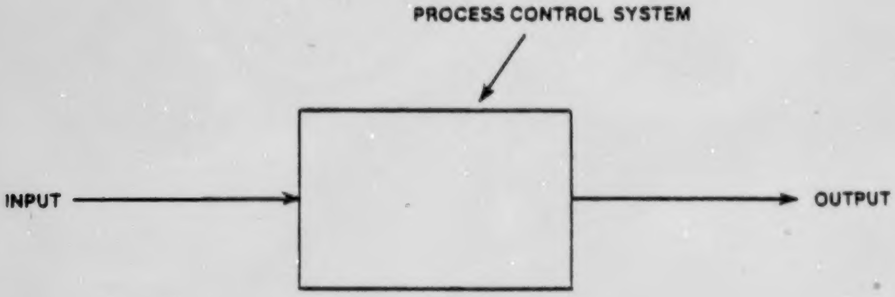


Figure 34-4-1. Transfer function of a system.

TOTAL LOOP GAIN

Overall system gain is the product of the gain of the individual components. The components that determine the total loop gain in a control loop are –

- Transmitter gain, mA/ft of level.
- Controller gain, mA/mA.
- Valve actuator (diaphragm) gain, inches/psi.
- Pipe and valve gain, gpm/inch.

- Process gain, ft of level/gpm.
- Signal transducer gain, psi/mA.

Total loop gain = (mA/ft) (mA/mA) (inches/psi) (gpm/inch) (ft/gpm) (psi/mA). All units in the above expression cancel; therefore, total loop gain is a dimensionless ratio that relates input to output.

TRANSMITTER GAIN

The gain of a transmitter is expressed as the ratio of the transmitter to the process measurement. Ratio is determined by the range of the transmitter; and although it is a variable used to determine or fix the total loop gain, it is a determining factor in the loop gain. The range of a transmitter is set to measure a process within desired limits. For example, a water tank could be 100 ft high, and the range of the transmitter could be 25 ft to 75 ft, with a 50-ft span (Figure 34-4-2). In this example, the gain of the transmitter is —

$$\frac{4\text{-}20\ \text{mA}}{25\text{-}75\ \text{ft}} = \frac{16\ \text{mA}}{50\ \text{ft}} = \frac{0.32\ \text{mA}}{\text{ft}}.$$

For the level process, transmitter gain is linear because every ft of level change causes transmitter output to change 0.32 mA. A flow process using a d/p cell as a transmitter does not have a linear gain because the relationship between flow and transmitter output is a square root function in accordance with Equation 34-4-1.

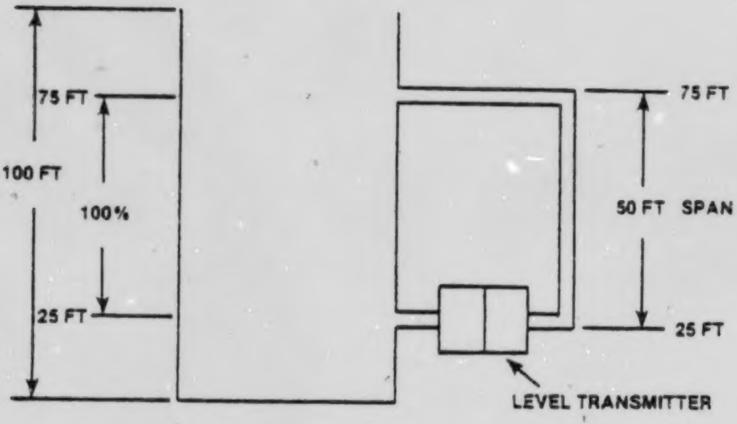

75 FT
100 FT
100%
25 FT
75 FT
50 FT SPAN
25 FT
LEVEL TRANSMITTER

Figure 34-4-2. Level process, indicating gain of a transmitter.

$$Q = K A \sqrt{\Delta P}$$ Equation 34-4-1 (Equation = Eq.)

where:

Q = flow.
K = constants.
A = area of differential producer.
ΔP = differential pressure developed across the differential producer.

The relationship between output of the flow transmitter and flow is different at every flow value. Total loop gain of a flow process, therefore, depends upon the flow. This is a significant consideration in controller tuning and will be discussed later.

CONTROLLER GAIN

Controller gain determines the relationship between input and output (gain = $\frac{\text{output}}{\text{input}}$). It is the only component gain that can be conveniently changed and is set at a value to establish the total loop gain at a point for optimum control. This is one of the values set by controller tuning.

VALVE ACTUATOR (POSITIONER) GAIN

In most process applications, the valve actuator or positioner gain is 1 and does not affect total loop gain. This means that a 4- to 20-mA signal change from the controller to the valve actuator causes the valve to respond 100% of its total travel. For applications in which positioners produce a full travel from signal changes other than 100% from the controller, the positioner gain will affect the total loop gain. Applications of this kind are uncommon in the nuclear industry.

VALVE GAIN

The valve setting coefficient that relates the valve opening to flow through the valve is known as the "valve gain," which normally is a nonlinear relationship because of the particular valve characteristic and valve sizing. Valve gain is a function of a valve opening and should be considered to be a constant value around the normal control point of the process.

PROCESS GAIN

The valve is a function of the process itself and is determined by the physical characteristics of the process. In some situations, the valve is a constant linear function, as in the level process of Figure 34-4-2. If level is to be controlled in a spherical tank or one whose sides are not perpendicular, the process gain would depend upon the point of control. Many temperature and reaction processes, not common in nuclear power plants, are very nonlinear and present difficult control situations.

SIGNAL TRANSDUCER GAIN

The most common example of transducer application is found in conversion of an electronic signal from an electronic controller to a linear pneumatic signal that operates a control valve. Most conventional control loops employed in nuclear power plants are electronic, having electronic transmitters and controllers. Most control valves in such control loops are pneumatic because of reliability and fail-safe operation. Transducers that convert the electronic signal from a controller to a proportional pneumatic signal for valve operation are considered to have a gain of unity in the control loop. The block diagram of a control loop in Figure 34-4-3 represents the gain relationship of each component in the control system.

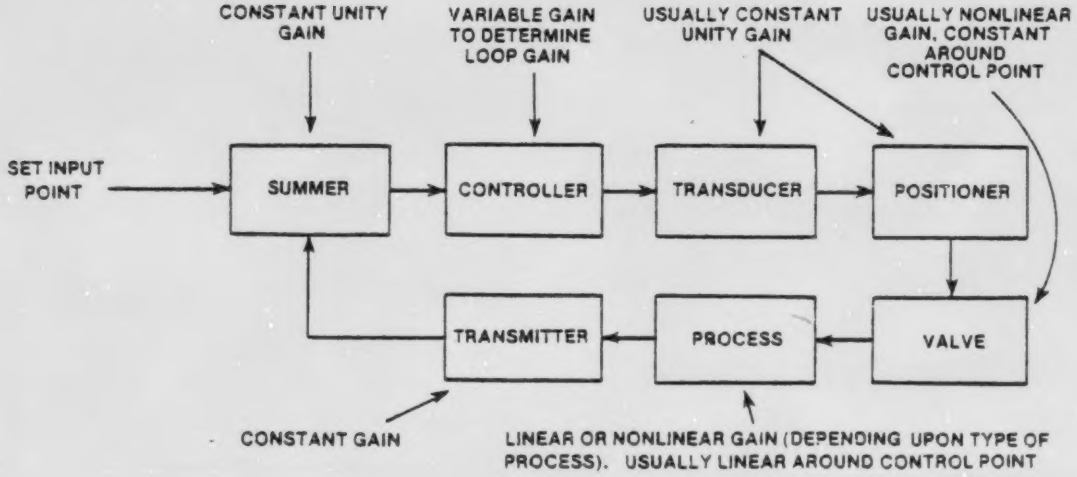

CONSTANT UNITY GAIN
VARIABLE GAIN TO DETERMINE LOOP GAIN
USUALLY CONSTANT UNITY GAIN
USUALLY NONLINEAR GAIN, CONSTANT AROUND CONTROL POINT
SET INPUT POINT
SUMMER
CONTROLLER
TRANSDUCER
POSITIONER
TRANSMITTER
PROCESS
VALVE
CONSTANT GAIN
LINEAR OR NONLINEAR GAIN (DEPENDING UPON TYPE OF PROCESS). USUALLY LINEAR AROUND CONTROL POINT

Figure 34-4-3. Gain components in a closed-loop control system.

TOTAL LOOP GAIN

Regardless of the combination of gain components in a control system, total loop gain always should be slightly less than unity to produce the best process response and to maintain process stability. The process response curves in Figure 34-4-4 relate process reaction and process gain. The curves indicate a response to a step change on the input (set point) and the corresponding process response. In each curve, a step change was introduced into a stable system at T_0 when the process was at set point (SP = PV).

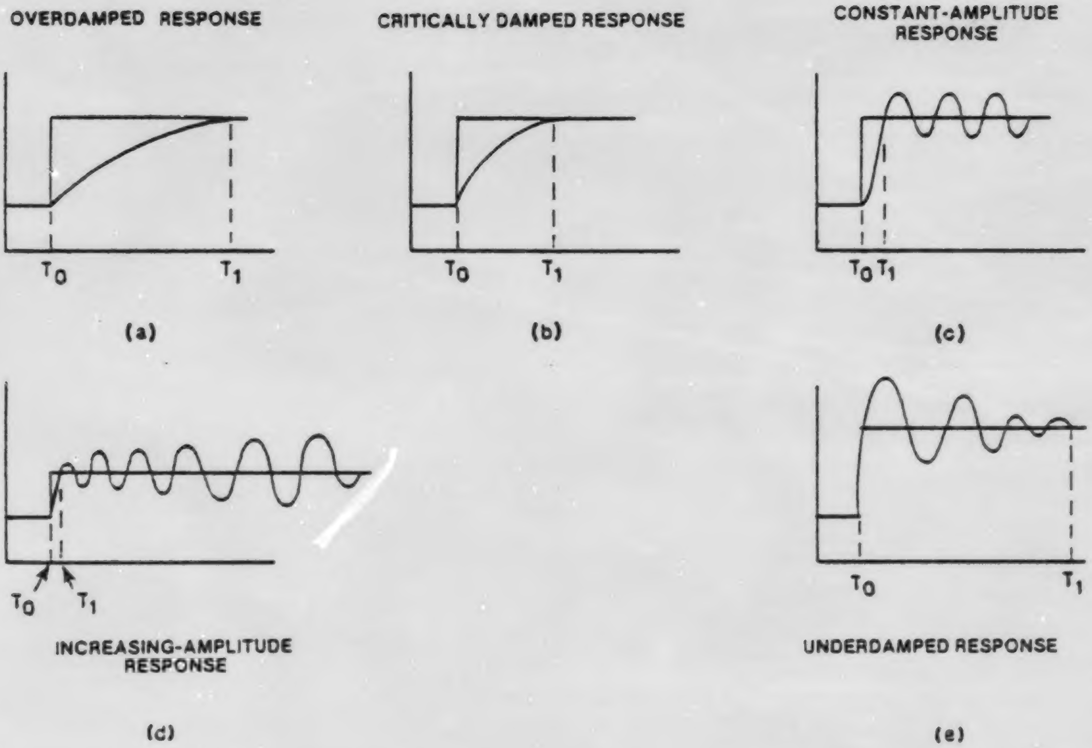

OVERDAMPED RESPONSE
T0
T1
(a)
CRITICALLY DAMPED RESPONSE
T0
T1
(b)
CONSTANT-AMPLITUDE RESPONSE
T0 T1
(c)
T0
T1
INCREASING-AMPLITUDE RESPONSE
(d)
T0
T1
UNDERDAMPED RESPONSE
(e)

Figure 34-4-4. Process response to a step change.

OVERDAMPED RESPONSE

The control system is overdamped in Figure 34-4-4a. The process returns to set point, but the required time duration (T_1, T_0) is maximum. This represents a safe response, however, because the process changes very slowly and does not overshoot the set point. Total loop gain for this situation is too low for most control situations.

CRITICALLY DAMPED RESPONSE

The response in Figure 34-4-4b represents a critically damped loop because the loop gain is maximum, producing a minimum time duration during which the process is away from set point and not causing overshoot. This is an optimum control situation in which overshoot and cycling of the process are not desired.

CONSTANT- AND INCREASING-AMPLITUDE RESPONSE

Response curves in Figure 34-4-4c and d represent unacceptable situations for process control. The total loop gain in each case is too high, producing process instability, which usually cannot be tolerated. This control characteristic signifies very poor control quality.

UNDERDAMPED, OR QUARTER-AMPLITUDE, DECAY DAMPING

The response in Figure 34-4-4e represents a control criteria that produces a damped cyclic response to a disturbance. This type of response pattern gives neither minimum deviation nor minimum duration, but for processes that can tolerate overshoot, it is used as a criterion for optimum control. Loop tuning is such that each deviation peak is reduced one quarter from the preceding peak. At the end of four cycles, the process is back at set point. This situation is desirable because the area bounded by the curve showing deviation from set point is less than for any of the other responses. Where overshoot is permissible, loops normally are tuned for this response. The purpose of controller tuning is to find the control-mode setting, which normally is quarter-amplitude decay damping, that will yield the optimum control situation.

CONTROLLER TUNING

As previously mentioned, the purpose of controller tuning is to adjust control-mode settings at a value that will give the best control for a given situation. Many approaches have been used to accomplish this – some analytical and some empirical. Analytical methods are based upon known transfer functions of the process and the other components in the loop. Empirical methods rely upon measurements made on the system during times of normal operation and are employed to determine data from which control-mode settings are calculated.

OPEN-LOOP TRANSIENT RESPONSE, OR PROCESS REACTION, METHOD

This method of determining proper control-mode settings was developed by T.G. Zielger and N.B. Nichols. The basic approach is to open the process loop and to place the controller in the manual mode of operation in order that no control action occurs. This procedure allows study of the transfer function of the process but not of the controller. With the process in a stable mode of operation, a small disturbance is initiated, usually a step change in the final control element. The process reaction, a measurement of the process plotted against time, is used to obtain data for empirically-derived formulas with which the control mode settings can be determined. The process-reaction plot in Figure 34-4-5 provides information employed in the determination of control-mode settings.

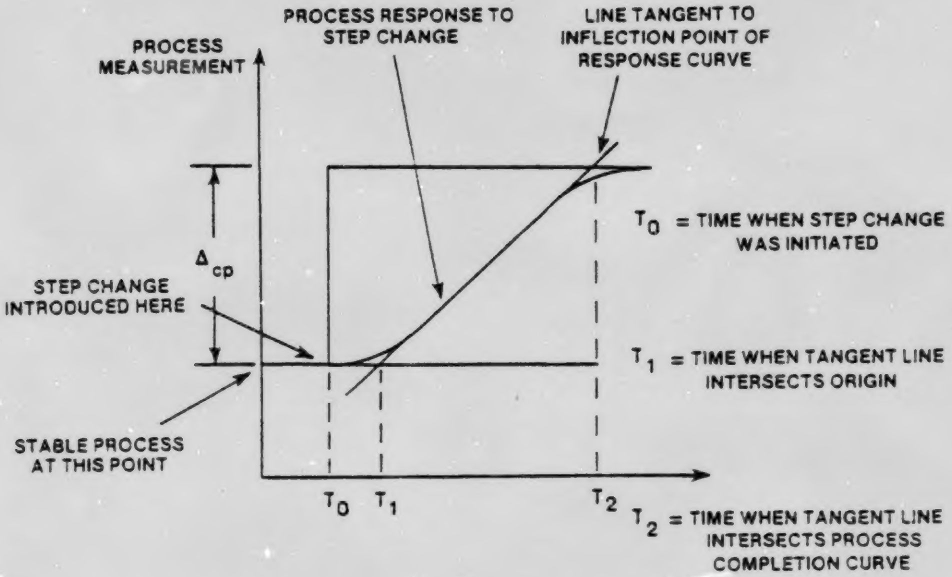

PROCESS MEASUREMENT
PROCESS RESPONSE TO STEP CHANGE
LINE TANGENT TO INFLECTION POINT OF RESPONSE CURVE
Δ_{cp}
STEP CHANGE INTRODUCED HERE
STABLE PROCESS AT THIS POINT
T_0 = TIME WHEN STEP CHANGE WAS INITIATED
T_1 = TIME WHEN TANGENT LINE INTERSECTS ORIGIN
T_2 = TIME WHEN TANGENT LINE INTERSECTS PROCESS COMPLETION CURVE
T_0
T_1
T_2

Figure 34-4-5. Data from process response curve for controller tuning.

Values taken from the response curve used for calculation of control-mode settings are:

1. L = lag time in minute = $T_1 - T_0$.
2. ΔC_s = step change in percent of full scale measurement.
3. N = rate of change = percent of change.
4. T = change time of the process in minutes.
   $T = T_2 - T_1$.

5. ΔC_v (not shown on the curve) = percent of change in controlling variable change.

6. R = a unitless ratio = $\frac{NL}{\Delta C_s}$

The control mode settings are derived from the following equations:

Proportional Mode –

$$K_p = \frac{\Delta C_v}{NL} \qquad \text{Eq. 34-4-2}$$

where:

K_p is the proportional gain of the controller.

ΔC_v, N, L are as previously described.

Proportional plus reset control –

$$K_p = 0.9 \frac{\Delta C_v}{NL} \qquad \text{Eq. 34-4-3}$$

$$T_R = \text{reset time} = 3.33 L \qquad \text{Eq. 34-4-4}$$

where:

T_R = is the reset time in minutes –

Proportional plus reset plus derivative:

$$K_p = 1.2 \frac{\Delta C_v}{NL} \qquad \text{Eq. 34-4-5}$$

$$T_R = 2\ L \qquad \text{Eq. 34-4-6}$$

$$T_o = 0.5\ L$$

where:

T_o is the derivative time in minutes.

The above calculations will provide settings used for critically damped tuning. When quarter-amplitude damping is desired, the proper setting for the control modes should be determined from the following equations:

Proportional —

$$K_p = \frac{\Delta C_v}{NL} \left(1 + 0.33 \frac{NL}{\Delta C_s}\right) \qquad \text{Eq. 34-4-7}$$

Proportional plus reset —

$$K_p = \frac{\Delta C_v}{NL} \left(0.9 + \frac{R}{12}\right) \qquad \text{Eq. 34-4-8}$$

$$T_R = \left(\frac{30 + 3R}{9 + 20R}\right) L \qquad \text{Eq. 34-4-9}$$

Proportional plus reset plus derivative –

$$K_p = \frac{\Delta C_V}{NL} \left(1.33 + \frac{R}{4}\right) \qquad \text{Eq. 34-4-10}$$

$$T_R = \left(\frac{32}{13} + \frac{6R}{8R}\right) L \qquad \text{Eq. 34-4-11}$$

$$T_o = L \left(\frac{4}{11 + 2R}\right) \qquad \text{Eq. 34-4-12}$$

EXAMPLE

Given: A process response curve similar to the one in Figure 34-4-5 gives the following values:

$L = 0.3$ min.
$\Delta C_S = 4\%$.
$T = 2.8$ min.
$\Delta C_V = 10\%$.

Find: Control-mode settings for a proportional-plus-reset-plus-derivative controller for (1) critical damping and for (2) quarter-amplitude damping.

Solution: (1) Use the equations for critical damping:

$$K_p = 1.2\,\frac{\Delta C_V}{NL} \text{ and } N = \frac{\Delta C_s}{T}$$

$$N = \frac{4\%}{2.8 \text{ min}}$$

$$N = 1.43\%/\text{min}$$

$$K_p = \frac{\Delta C_V}{NL}$$

$$= \frac{10\%}{1.43\%/\text{min } (0.3 \text{ min})}$$

$$= \frac{10\%}{(1.43\ (0.3)}\ (\text{min}/70)\ (\frac{1}{\text{min}})$$

$$= \frac{10}{0.47}$$

$$K_p = 21.$$

$$T_R = 2\ L$$

$$= (2)\ (0.3 \text{ min})$$

$$T_R = 0.6 \text{ min.}$$

$$T_o = 0.5\ L$$

$$= (0.5)\ (0.3 \text{ min})$$

$$T_o = 0.15 \text{ min.}$$

(2) For quarter-amplitude damping —

$$K_p = \frac{\Delta C_V}{NL}\ (1.33 + \frac{R}{4})$$

$$R = \frac{NL}{\Delta C_s}$$

$$= \frac{(1.43\%/\text{min})\ (0.3 \text{ min})}{4\%}$$

$$R = 0.107$$

$$K_p = (\frac{10\%}{0.429})\ (1.33 + \frac{0.107}{4})$$

$$K_p = (\frac{10}{0.429})\ (\frac{5.449}{4})$$

$$= \frac{54.49}{1.716}$$

$$K_p = 31.75.$$

$$T_R = (\frac{32}{13} + \frac{6\ R}{8\ R})\ L$$

$$= [\frac{32}{13} + \frac{6\ (0.107)}{8\ (0.107)}]\ L$$

$$= (2.46 + 0.75)\ (0.3)$$

$$T_R = 0.963 \text{ min.}$$

$$T_O = L\ (\frac{4}{11 + 2\ R})$$

$$= 0.3 \text{ min } [\frac{4}{11 + 2\ (0.107)}]$$

$$T_O = 0.356 \text{ min.}$$

The foregoing Example demonstrates that —

- A greater gain is required for quarter-amplitude damping than for critical damping.
- As gain is increased, the need for reset is decreased. Reset here is measured in minutes/repeat. Actual reset value in repeats/minute decreases as the minutes increase.
- More derivative can be used when overshoot, which accompanies quarter-amplitude damping, can be tolerated.
- Quarter-amplitude damping produces a better control quality than critical damping.

ULTIMATE-CYCLE, OR ULTIMATE-SENSITIVITY, METHODS

The control-loop tuning method just described — open-loop transient response — utilizes values derived from the process transfer characteristics. Ziegler and Nichols developed another technique that incorporates the controller transfer function as well as that of the process. It is termed the "ultimate-cycle method" because it is based upon (1) adjustment of a loop until oscillations occur (the ultimate sensitivity) and upon (2) determination of the control-mode settings from conditions that produced the cycles.

The following steps are required for this method of tuning:

1. With the control loop on stable open-loop (manual) control, remove all reset and derivative action.
2. Reduce controller gain to its minimum value.
3. Place the controller into the automatic control mode to provide closed-loop control.
4. Gradually increase proportional gain of the controller until oscillations of the process just begin. Small disturbances may have to be introduced into the system to cause it to oscillate: This can be accomplished by means of small changes in the set point.
5. Note the critical gain (K_c), which produced the oscillations.
6. Note the critical period of oscillations (T_c). From K_c and T_c, the control-mode settings are determined from these equations:

a. Proportional –

$$K_p = 0.5\ K_c \qquad \text{Eq. 34-4-13}$$

Equation 34-4-13 is for critical damping. For quarter-amplitude damping, the gain is increased for a quarter-amplitude dynamic response; this is true for each of the cases in b and c below.

b. Proportional plus reset –

For critical damping

$$K_p = 0.45\ K_c \qquad \text{Eq. 34-4-14}$$

$$R_T = T_c/1.2 \qquad \text{Eq. 34-4-15}$$

For quarter-amplitude damping

$$T_R = T_c \qquad \text{Eq. 34-4-16}$$

c. Proportional plus reset plus derivative –

For critical damping

$$K_p = 0.6\ K_c \qquad \text{Eq. 34-4-17}$$

$$T_R = T_c/2.0 \qquad \text{Eq. 34-4-18}$$

$$T_D = T_c/8 \qquad \text{Eq. 34-4-19}$$

For quarter-amplitude damping

$$T_R = T_c/1.5 \qquad \text{Eq. 34-4-20}$$

$$T_D = T_c/6 \qquad \text{Eq. 34-4-21}$$

The process reponse plot in Figure 34-4-6 is used to obtain data for calculation of control-mode settings.

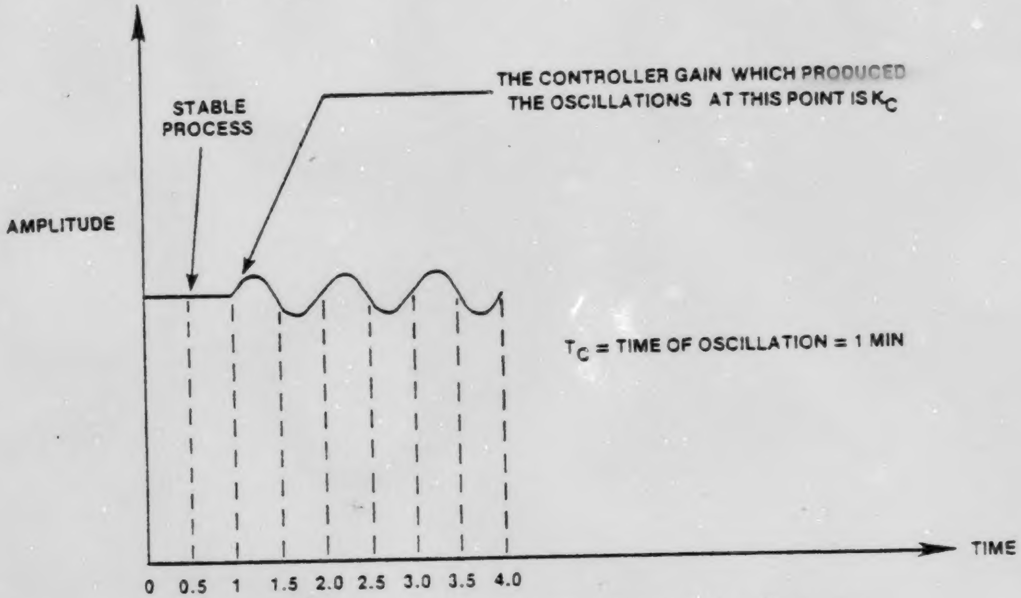


Figure 34-4-6. Process response plot to determine T_c and K_c.

EXAMPLE

Given: $T_C = 6.3$
$K_C = 2.2$
These values were taken from a response curve similar to the one in Figure 34-4-6.

Find: The control-mode settings for proportional-plus-reset-plus-derivative controller that will produce quarter-amplitude damping.

Solution: Use Equations 34-4-19, 34-4-20, and 34-4-21:

$$T_D = T_C/8$$

For quarter-amplitude damping –

$$T_R = T_C/1.5$$

$$T_D = T_C/6$$

EXAMPLE

Given: In an application of the procedures outlined above for the ultimate-cycle method, the critical time T_C was found to be 6.3 min, and the critical gain K_C was 2.2

Find: The control-mode settings for proportional-plus-reset-plus-derivative for quarter-amplitude damping.

Solution: Employ Equations 34-4-17, 34-4-20, and 34-4-21:

Proportional –

$$K_p = 0.6\ K_c$$
$$= 0.6\ (2.2)$$
$$K_p = 1.32.$$

Reset –

$$T_R = T_c/1.5$$
$$= 6.3/1.5$$
$$T_R = 4.22 \text{ min/repeat.}$$

Derivative –

$$T_D = T_c/6$$
$$= 6.3/6$$
$$T_D = 1.05 \text{ min.}$$

FREQUENCY RESPONSE METHOD OF CONTROLLER TUNING

The previously discussed methods of controller tuning were based upon the study of process dynamics that result from a stable system's response to a step input. The step input produces a change in process output that varies with time. The slope of the ramp function is used to determine the control-mode settings. For a sine wave input to a process, no simple description that explains the physical process response exists. However, for linear systems, the output signal for a sine wave input must be a sine wave of the same frequncy as that of the input. The method with which the input and output signals are obtained is depicted in Figure 34-4-7.

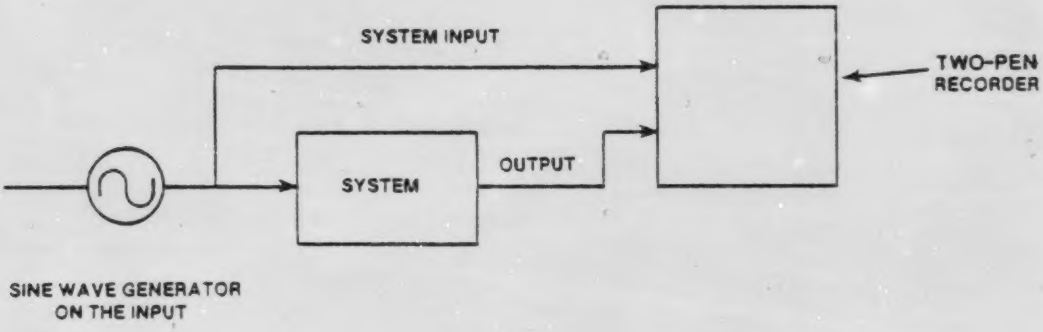

SYSTEM INPUT
TWO-PEN RECORDER
OUTPUT
SYSTEM
SINE WAVE GENERATOR ON THE INPUT

Figure 34-4-7. Method to obtain frequency response data.

Response for the input and output of the two-pen-recorder plotting system is illustrated in Figure 34-4-8.

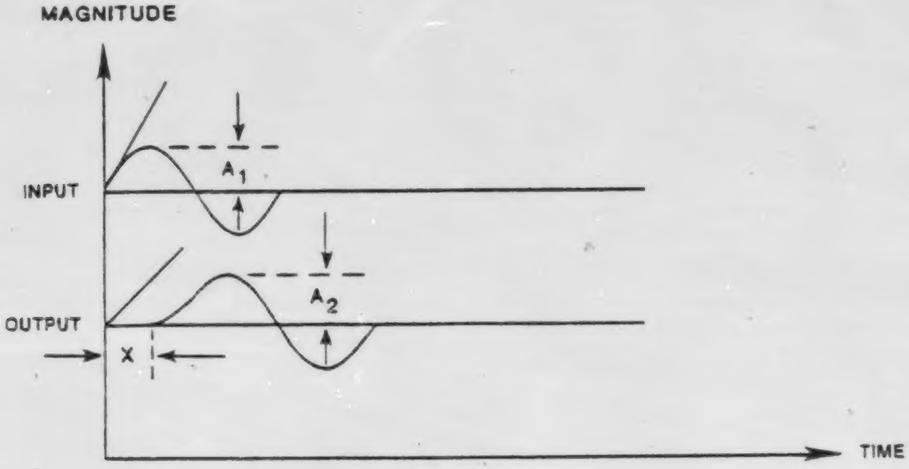


Figure 34-4-8. Input and output response for a linear system.

The initial slope of the sine-wave input is approximated by a ramp input — the final result being a transite response followed by a steady-state sine-wave response. If input frequency is very low, the period of the sine wave will be very long. The period, thus, is very much longer than the system time constant. Under this condition, output will have sufficient time to approach a condition nearly in equilibrium with the input signal. Magnitude and phase angle of the input at low frequencies will be equal to that of the output. As frequency of the input increases, however, the period decreases, and the system will not have time to achieve an equilibrium between input and output. Under such conditions, output magnitude will decrease; and the output phase angle will lag the input phase angle. The input-signal frequency can be sufficiently high that the output-signal response is negligible. Any frequency ratio solution then must show a decrease in the ratio of output to input magnitude with increase in frequency. Also, the difference between input and output phase angle is lagging or negative with frequency increases.

A variable-frequency sine-wave generator and a two-pen recorder are used to obtain a frequency response (Figure 34-4-7). The generator is set to a particular frequency. Both the input and the output signals are recorded. Steady-state sine-wave plots for a particular frequency are illustrated in Figure 34-4-8. Magnitude and phase angle at this particular frequency can be calculated from Equations 34-4-22, 34-4-23, and 34-4-24.

$$M = \frac{A_2}{A} \qquad \text{Eq. 34-4-22}$$

where:

M = magnitude ratio.

A_2 = output amplitude.

A_1 = input amplitude.

$$\theta = 360° \left(\frac{x}{p}\right) \qquad \text{Eq. 34-4-23}$$

where:

θ = phase angle in degrees.

x = lag measurement.

p = period of the waveform, time per cycle.

$$f = \frac{N}{P} \qquad \text{Eq. 34-4-24}$$

where:

N = recorder chart speed, in inches/second.

f = waveform frequency, in cycles per unit time (cycles/second).

P = period measurement of the waveform, in chart units per cycle.

Frequency response of a system is determined by observation of data at several different frequencies. The response data then are plotted in terms of a Bode plot or diagram in which the magnitude is plotted on one axis and frequency plotted on the other axis, by use of log-log coordinates.

To ensure that process stability is achieved, the gain at the -180° frequency must be a safe distance below one; and the phase angle at this gain must be a safe distance above -180°. The first safety margin is the gain margin; the second is the phase margin. The gain and phase margins are indicated in Figure 34-4-9. Controller tuning procedures with the frequency response method involve adjustment of the control-mode settings to modify the open-loop Bode diagram for optimum control.

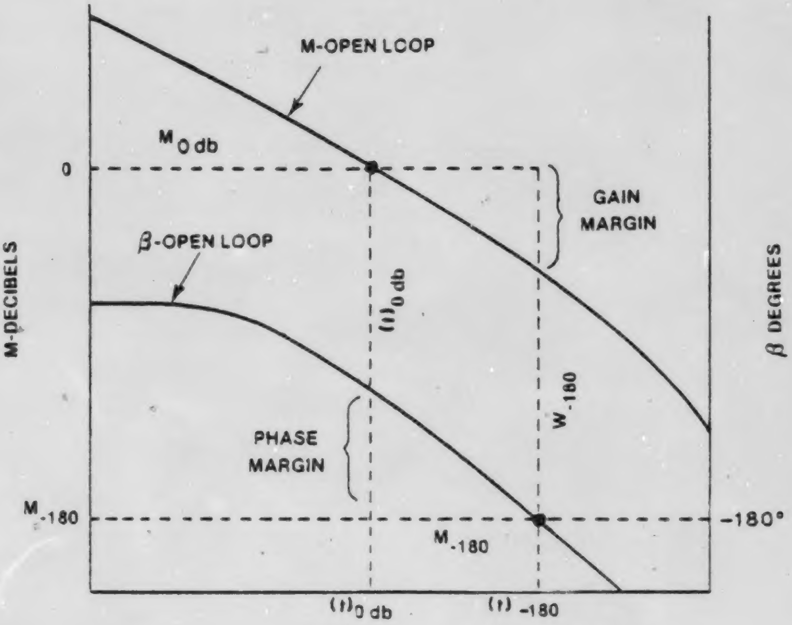


Figure 34-4-9. Gain and phase margins from a Bode diagram.

The controller gain is used to adjust the open-loop gain plot without changing the phase plot and is adjusted until the gain and phase margins are satisfied. The derivative mode increases the phase margin to a desired amount, and the integral mode is adjusted to reduce the phase margin. Although the frequency response method of process dynamic analysis is helpful in the design of process equipment and controllers, it is not used in the actual practice of tuning controllers because of its complexity.

TRIAL-AND-ERROR METHOD OF CONTROLLER TUNING

A modification of the ultimate-cycle method previously discussed is very commonly used by practicing technicians to tune controllers. Although referred to as "trial-and-error," the method is more exact than the name implies. This technique is based upon Ziegler and Nichols' ultimate-cycle method and is valid because the control-mode settings are made while the process response is being observed.

This method of setting the control modes involves removal of the reset, or integral, control action and the derivative control action from the controller. Removal is accomplished with the control loop in open-loop control. For this situation, the controller gain is reduced to a low value. With the process stable, the controller is switched to the automatic mode to provide closed-loop control. Controller gain then is increased by small increments until process instability, evident by small oscillations in the process measurement, is detected. The setting that produces oscillation usually is doubled, and the next items are decreased in small amounts. After each adjustment, the system must be upset to produce an oscillation. When the process is again stable, the reset action is increased until process instability again is just detected. Reduce reset action slightly. The reset adjustment is decreased in order to increase the reset action when the reset units are minutes per repeat.

For controllers that have the reset units given in minutes per repeat, an increase in the reset setting will decrease this reset action. Remember that gain and proportional band are inversely related: An increase in gain is the same as a decrease in proportional band, and an increase in proportional band is the same as a decrease in gain. When proportional gain and reset have been adjusted, derivative is added in small increments until process instability is just detected. The derivative setting then is decreased slightly. After the control-mode adjustments have been made, small disturbances should be introduced into the system to check the quality of control. Disturbances can be introduced by small changes made in the controller set point. The settings then should be modified to obtain quarter-amplitude damping.

While the controller is being adjusted to the process by the control-mode settings, small variations in the process are necessary. The disturbances are necessary to determine whether or not the controller is responding to process load changes. Regardless of the method used to tune a controller, the test of an optimally-tuned system is the ability of a controller to maintain process conditions when load changes occur.

When a controller is properly tuned to a process, further tuning or retuning may be necessary when conditions change. A major change in the operating point of the process may result in a change in the control valve or process gain since these components usually are nonlinear and since the gain depends upon the operating point. A change in the range of the transmitter that monitors the process also will change the total loop gain, which can require a retuning of the controller. For example, if the range of transmitter were increased by a factor of two, the controller gain would need to be decreased by one-half to maintain the same total loop gain and quality of control.

EXERCISES

1. Using the open-loop process response method for the following data, calculate the control-mode settings for critical dampings. Assume a proportional-plus-reset-plus-derivative controller:

   $L = 0.5$ min.
   $\Delta C_S = 6\%$.
   $T = 4.0$ min.
   $\Delta C_V = 8\%$.

2. Repeat Exercise 1 for quarter-amplitude damping.
3. Compare answers in Exercise 1 and 2; explain the reason for the differences.

MATERIALS

2 control valves with the following specifications:
    3/4" body.
    Pneumatic operated, 3-15 psig.
    Fisher 512 RGS.
2 d/c cells, pneumatic with adjustable input range of 0-250 inches of water. Output range 3-15 psig. Foxboro 13A.

2 controllers with fast and slow chart drive. Pneumatic with proportional, reset, and derivative. Foxboro Model 120.
1 orifice meter with 1/2" concentric orifice. Perry Equipment Co. Type 1480.
1 pump, 3/4" with 1/2 hp motor. Jacuzy 3 RM 254A.
1 tank to be used for process.
8 ft of 12" I.P. PVC pipe capped at each end with appropriate fittings for pump and instrument connections.
1 tank to be used as a reservoir approximately 50-gal capacity.
Manufacturer's instruction booklet for instruments and equipment.
Assorted piping, tubing, and wire for equipment connections.

PROCEDURES

1. Follow manufacturer's recommended installation and start-up procedures; connect the equipment to construct a flow-level process as illustrated in Figure 34-4-10.
2. With both controllers on manual, stroke each valve to determine valve operation at either air-to-open or air-to-close. Fill reservoir with water.
3. Select proper controller action to provide negative feedback in the control loop. Set controller on the proper action as direct or reverse.
4. Close both valves; start pump.
5. Open flow control valve; adjust for approximately 50% flow on the flow controller.

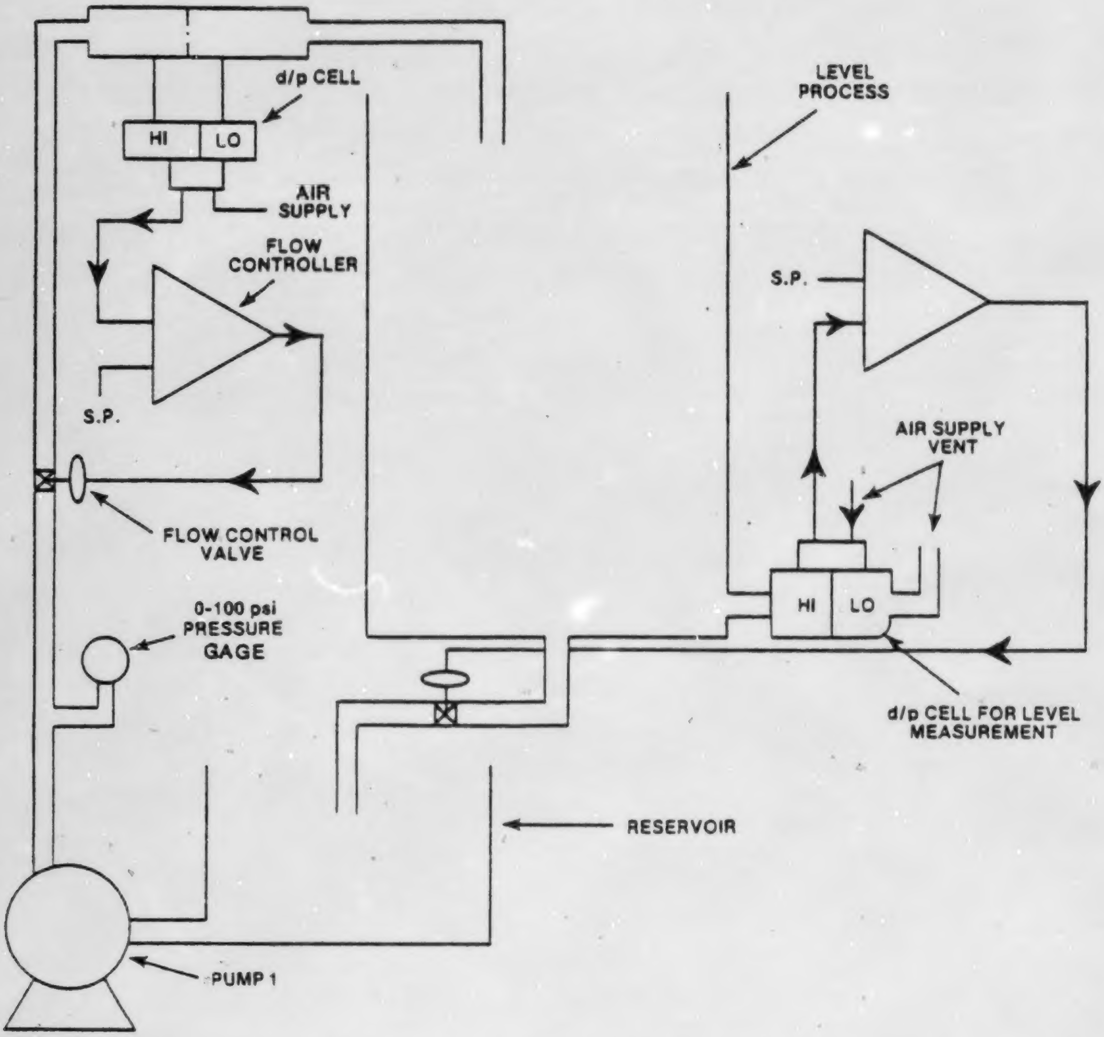

d/p CELL
HI
LO
AIR SUPPLY
FLOW CONTROLLER
S.P.
FLOW CONTROL VALVE
0-100 psi PRESSURE GAGE
LEVEL PROCESS
S.P.
AIR SUPPLY VENT
HI
LO
d/p CELL FOR LEVEL MEASUREMENT
RESERVOIR
PUMP 1

Figure 34-4-10. Flow level process.

6. Open level-control valve; adjust for approximately 50% level as indicated by the level controller.
7. Using the open-loop response method of controller tuning, determine proper control-mode settings for the level and flow controller. List the settings in Data Table 34-4-1.

Adust control-mode settings for the valve; check for optimum control. This is trial 1.

8. Using the ultimate-sensitivity, or ultimate-cycle, method of controller tuning, determine control mode settings for each control. List settings in Data Table 34-4-1. Adjust mode settings for these valves and check for optimum control. This is trial 2.
9. Use trial-and-error method of controller tuning to determine control-mode settings; list settings in Data Table 34-4-1. This is trial 3.
10. Place both controllers in the manual mode of operation; close both valves; and stop pump 1. The experiment is now complete.

DATA TABLES

DATA TABLE 34-4-1

CONTROL-MODE SETTINGS

	Proportional	Reset	Derivative
Trial 1			
Trial 2			
Trial 3			

REFERENCE MATERIALS

Bateson, Robert. Introduction to Control System Technology. Columbus, OH: Charles E. Merrill Publishing Company, 1973.

Ziegler, T.G. and Nichols, N.B. ASME Transactions. November, 1942.

Zoss, Leslie M. Applied Instrumentation in the Process Industries. Volume IV: Control Systems; Theory, Troubleshooting, and Design. Houston: Gulf Publishing Company, 1979.

TEST

1. Explain the purpose of controller tuning.

2. List and explain three methods of controller tuning.

3. List components that determine the total loop gain of a control system.

4. From results of the procedure portion of this module and observations of Data Table 34-4-1, which procedure of controller tuning is more exact? Which procedure is easier?

5. Define the following terms:
   a. Critical damping.

   b. Overdamped response.

   c. Underdamped response.

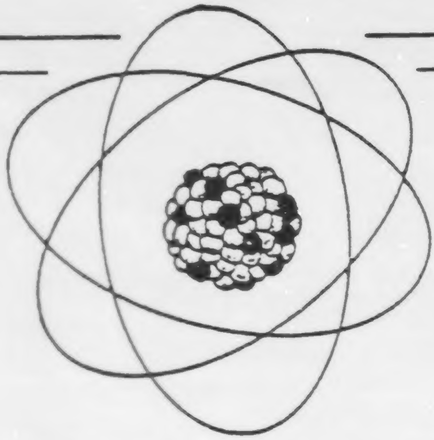
   d. Overshoot.

   e. Oscillation.

6. What is a good test for optimum control?

7. Use the ultimate-sensitivity method to determine control-mode settings for a proportional-plus-reset-plus-derivative controller for the following data. Assume critical damping.
$T_C = 4.8$.
$K_C = 1.6$.

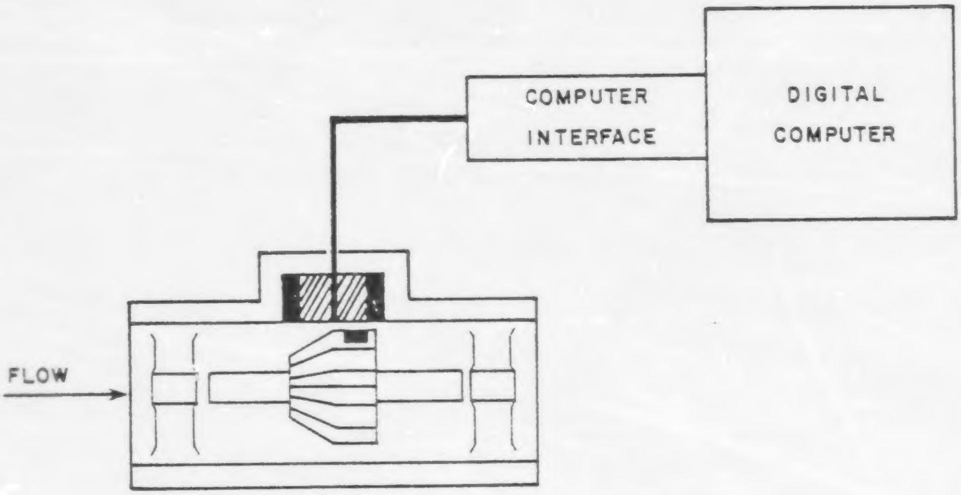
8. Repeat test item 4 for quarter-amplitude damping.



NUCLEAR TECHNOLOGY

MODULE 34 - 5

OPERATIONAL AMPLIFIERS


COMPUTER
INTERFACE
DIGITAL
COMPUTER
FLOW

CONTROL SYSTEMS II
COURSE 34

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

COURSE MODULES

CONTENTS

COURSE 34 CONTROL SYSTEMS II

MODULE 34-1 Introduction to Transfer Functions
MODULE 34-2 Frequency Response Analysis
MODULE 34-3 Combination Control Systems
MODULE 34-4 Controller Tuning
⇨ MODULE 34-5 Operational Amplifiers
MODULE 34-6 Microprocessor Utilization
MODULE 34-7 Microprocessor Programming

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INTRODUCTION

The wonders of modern technological advances have resulted in "gadgets" and "magic devices" that seem to have eliminated a true science fiction world. It is now difficult to separate fact from fiction in the world of applied sciences. A mathematical calculator, which two decades ago was found only in larger laboratories and engineering offices, has been replaced by hand-held calculators now used by students in junior high school. The first-generation electronic vacuum tube computers contained electronic components that would fill a room. The functions performed by such electronic beasts now can be carried out with a pocket calculator. The developments and improvements of such electronic devices have followed, to a large extent, the development of operational amplifiers. "Op amps," as they are called, are now available in a variety of small, inexpensive, packaged integrated circuits that provide limitless possibilities for application.

This module explains and describes the operation of op amps and discusses their use as integrators, differentiators, linear inverting and noninverting amplifiers.

MODULE PREREQUISITES

The student should have completed Course 3, "Principles of Process Instrumentation"; Course 6, "Instrumentation and Control of Reactors and Plant Systems"; Course 33, "Control Systems I"; and the previous modules of this Course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
    - Operational amplifier.
    - Op amp characteristics:
        - Open-loop gain.
        - Negative feedback.
        - Input resistance.
        - Output resistance.
        - Offset voltage.
        - Bias.
        - Terminals.
        - Inverting output.
        - Noninverting output.
2. Describe op amp operation and explain the use of op amps in the following:
    - Integrator.
    - Differential amplifier.
    - Differentiators.
    - Circuits for mathematical calculations.
3. Define and list the significances of the following op amp ratings:
    - Power requirements.
    - Common mode rejection ratio.
    - Supply voltage.
4. Given the input to an op amp without feedback, calculate the open-loop gain and the absolute maximum voltage available at the output.
5. Find the maximum input voltage that can be applied before clipping occurs.

The term "op amp" is used to describe an amplifier that has characteristics approaching an ideal amplifier. Although some of the ideal characteristics are difficult or impossible to obtain, ideal conditions often are assumed to exist in order to develop circuits and equations that work perfectly on paper. These circuits and equations then work very well on paper for a design approach. Actual op amp characteristics are, more or less, ideal relative to conditions external to the op amp itself.

WHAT IS AN OP AMP?

An op amp is a high-gain d.c. amplifier with two input leads and a single-ended output lead. The input is the voltage difference on the input leads, and the output voltage is developed across a resistive load connected to the output lead. The output voltage is larger than the input voltage by a factor equal to the amplifier gain (Figure 34-5-1). The amplifier voltage gain is determined from Equation 34-5-1.

$$A_{VOL} = \frac{V_o}{V_i}$$

Equation 34-5-1
(Equation = Eq.)

where:

A_{VOL} = amplifier voltage gain.
V_o = output voltage.
V_i = input voltage.

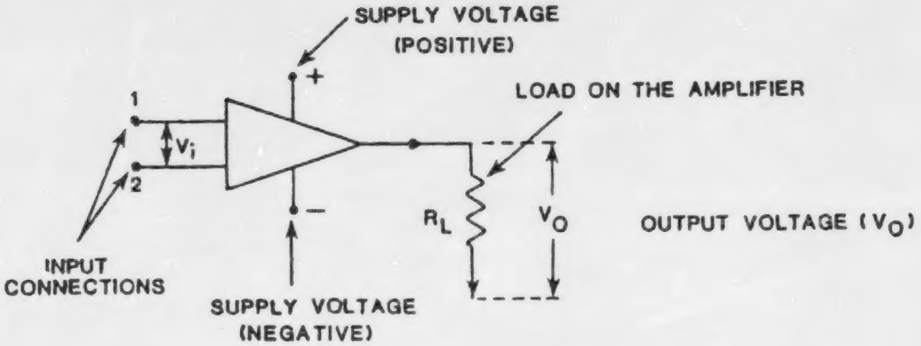
SUPPLY VOLTAGE (POSITIVE)
+
1
V_i
2
LOAD ON THE AMPLIFIER
–
R_L
V_O
OUTPUT VOLTAGE (V_O)
INPUT CONNECTIONS
SUPPLY VOLTAGE (NEGATIVE)

Figure 34-5-1. The typical op amp symbol.

An ideal amplifier is a somewhat mythical device that has the following characteristics:

- Infinite voltage gain.
- Infinite input impedance.
- Zero output impedance.
- $V_O = 0$ when $V_1 = V_2$.
- Infinite band pass capabilities.

OPEN-LOOP GAIN

The amplifier gain A_{VOL} is the open-loop voltage gain. This is the differential gain under conditions without the use of negative feedback. Negative feedback is used when a portion of the output signal is applied to the amplifier input in such a manner that the amplifier gain is reduced. The ideal open-loop gain is infinite. For this to be true, either the output must be infinitely large or the input voltage must be zero, according to Equation 34-5-1.

The concept of infinite gain is difficult to visualize because an infinite value is undefined. The important point to consider here is the fact that the output voltage must be very large when compared to the input voltage. Therefore, the input voltage is held to a very small value. The "infinite gain" of op amps is not an extremely large output voltage. The fact is that the output limits are slightly less than the positive and negative power supply voltage, which is normally less than 20 V. The open-loop gain limits are approximately between 5,000 and 100,000. The input voltage range for these values of gain is 0.0002 to 0.004 volts, with a maximum output of 20 volts. When the output voltage levels are considered to be signficiantly less than the assumed 20-V value for high-gain amplifiers, the input voltage level can approach zero, and the amplifier gain approaches infinity for nonzero values of output voltages.

EXAMPLE

Given: The gain of an op amp is 100,000. The output voltage is 2 volts.

Find: The input voltage.

Solution: Solve Equation 34-5-1 for V_i:

$$\begin{aligned} V_i &= \frac{V_O}{A_{VOL}} \\ &= \frac{2\ \text{V}}{100,000} \\ &= 0.00002 \text{ volts} \\ &= 20 \times 10^{-6} \text{ volts} \\ V_i &= 20\mu \text{ volts.} \end{aligned}$$

The number 1 input in Figure 34-5-1 is the inverting input, and the number 2 input is the noninverting input. V_i is the difference in these input voltage levels: $V_i = V_2 - V_1$. V_i usually is so small in op amp applications that practically no potential difference exists between the inverting and noninverting input.

INPUT RESISTANCE (R_i)

The input resistance of an op amp is the resistance between the two input leads, which are the inverting and noninverting inputs. This resistance should be very large in order that the current drain on the input source will be very low. Ideally, $R_i = \infty$. Practically speaking, however, values of R_i range from 5KΩ to 20MΩ, depending upon the type of op amp being considered and the operating parameters. The actual value of R_i is a function of the internal resistance of the signal source device. When high-resistance signal sources are used to supply the input current to drive the op amp, the resistance of the op amp should be relatively high. Conversely, when low-resistance signal sources are employed, the op amp input resistance should be low.

OUTPUT RESISTANCE (R_o)

When the differential input signal (V_i) is connected to the input, the op amp acts like a signal generator as seen by the output load. The output resistance (R_o) should be low in order that the output voltage appears across the load with very little dropped across R_o. Depending upon specific applications and op amp types, R_o value ranges are from a few ohms to a few hundred ohms. The effective output resistance is a function of, and is reduced by, feedback, which is employed in most op amp applications.

When properly applied, feedback can reduce the output resistance to near zero values. Feedback applications will be discussed in more detail later in this module. Figure 34-5-2 illustrates input and output resistance of an op amp. The A_{VOL} V_i term in Figure 34-5-2b represents the open-circuit voltage "generated" by the amplifier. Because R_o is zero, the output voltage can appear across R_L. If R_o were increased to the value of R_L, then half the output voltage would be dropped across R_o and half across R_L. This would represent a significant decrease in the efficiency of the amplifier.

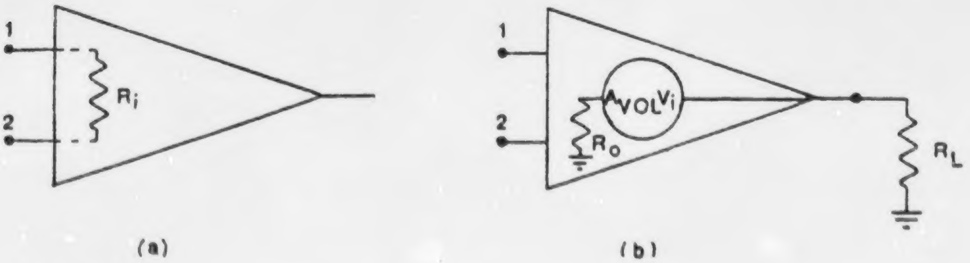

Figure 34-5-2. Op amp input and output resistance.

BANDWIDTH

The bandwidth, BW, of an amplifier is defined as "the range of frequencies at which the output voltage is no greater than 0.707 of its maximum value while the output voltage is held at a constant value." The ideal bandwidth is infinitely large, or starts at d.c. and extends to an infinite value of Hz. Again, achievement of such a criterion is impossible. The bandwidth capabilities fall short of this goal for most op amps. In fact, higher-frequency is a disadvantage of practical op amp circuit design, with the frequency range being from a few KHz to a MHz and with most applications falling in the lower end of this frequency spectrum.

OUTPUT OFFSET VOLTAGE

The output offset voltage (V_{oo}) is the output voltage to ground when the potential difference between the two input points is zero ($V_i = 0$). Since the internal circuitry of op amps is made up of several differential amplifiers, significant values of V_{oo} may exist because of the imbalances and inequalities in the different amplifiers. Without feedback, values of V_{oo} can be great enough to saturate the output or to drive the output nearly to the power supply level. This is not a serious problem in actual application, however, because op amps seldom are used without feedback or without some other simple corrective measure to prevent high values of V_{oo}. When the op amp output is zero (with $V_1 - V_2 = V_i = 0$), this amplifier is said to be in a "balanced," or "null," condition. In such a state, the op amp has ideal "common-mode rejection" (CMR) or "common-mode rejection ratio" (CMRR). Usually, the output common-mode voltage is from hundreds to thousands of times smaller than the output common-mode voltage.

RESPONSE TIME

The response time of an amplifier is the time required for the output to respond to a variation in input. Response time should be zero seconds, or the output should respond instantly to the input. "Slow rate" is a term that defines the response time of op amps and is the maximum change in output voltage that can be delivered per unit time. When changing, the output voltage is driven beyond the level at which it settles and is termed "overshoot" and overshoot is expressed as a percent of the steady-state voltage level, determined by Equation 34-5-2.

$$\text{Percent overshoot} = \frac{\text{amount of overshoot}}{\text{steady-state deflection}}\,(100)$$

Eq. 34-5-2

Response time and overshoot terms are clarified in Figure 34-5-3.

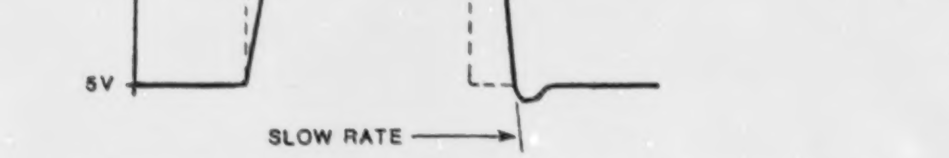

Figure 34-5-3. Typical response of op amp with unit gain to step input voltage.

EXAMPLE

Given: The steady-state output of an op amp is a 12-cm deflection on an oscilloscope. The overshoot response is 2 cm.

Find: Percent of overshoot.

Solution: From Equation 34-5-2 –

$$\text{Percent overshoot} = \frac{2\ \text{cm}}{12\ \text{cm}}\,(100)$$

$$= 0.1667 \times 100$$

$$\text{Percent overshoot} = 16.6790\%.$$

OP AMP POWER SUPPLY REQUIREMENTS

The output requirements of many op amp applications are such that V_o must be capable of swinging both above and below a reference level or of moving from positive and negative with respect to a ground or reference point. The d.c. power supply source then must be capable of driving the output in both directions as a plus-and-minus power supply is required. The power supplies for most op amps are plus-or-minus 15 V d.c., which means the output of the amplifier can swing from zero to 15 V d.c. in the positive and negative directions.

POWER SUPPLY REGULATION

The output voltage of most op amps will vary somewhat with power supply voltage variations. The amount of output variation with power supply voltage changes depends upon the closed-loop voltage gain and upon the amplifier sensitivity factor (S) listed in the manufacturer's specification sheets for a particular amplifier. An ideal op amp has a sensitivity factor of S = 0, which indicates that power supply voltage variations have no effect upon the output voltage. In reality, however, power supply regulation is required in order that the op amp output is responsive only to input voltage variations.

FEEDBACK CONSIDERATIONS

The open-loop voltage gain of an op amp without feeback (Equation 34-5-1) is very high, and the op amp output limited by the power supply voltage. Because of the high gain, small variations on the differential input voltage can saturate the op amp, drive the output to the power supply limit, and cause clipping and distortion of the output voltage. Op amps normally are thought of as linear operating devices, which means that V_o should proportionally follow V_i. The relationship between the two voltage levels is determined by the voltage gain of the device. Negative feedback is applied to the op amp by external circuits to reduce and regulate the voltage gain and to have a stabilizing effect upon operation.

Consider the open-loop, no feedback configuration shown in Figure 34-5-4 and the input and output waveforms in Figure 34-5-5. Notice that as the input signal becomes increasingly greater, the output increases to the point at which V_o approaches the power supply voltage and is "cut off"; that is, the extreme points of the sinusoidal waveform are clipped.

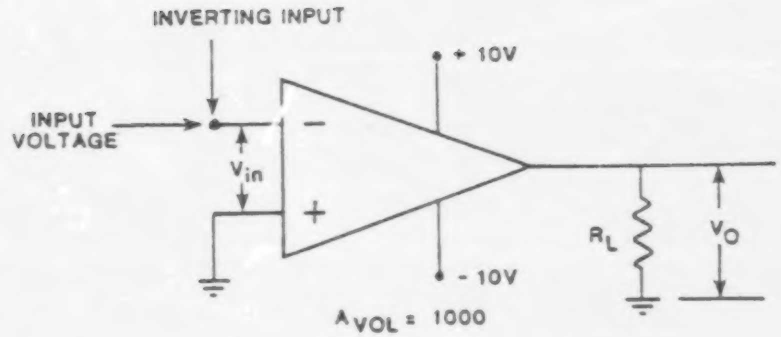
INVERTING INPUT
+ 10V
INPUT VOLTAGE
−
+
V in
R L
V O
- 10V
A VOL = 1000

Figure 34-5-4. Op amp without feedback but with inverting input.

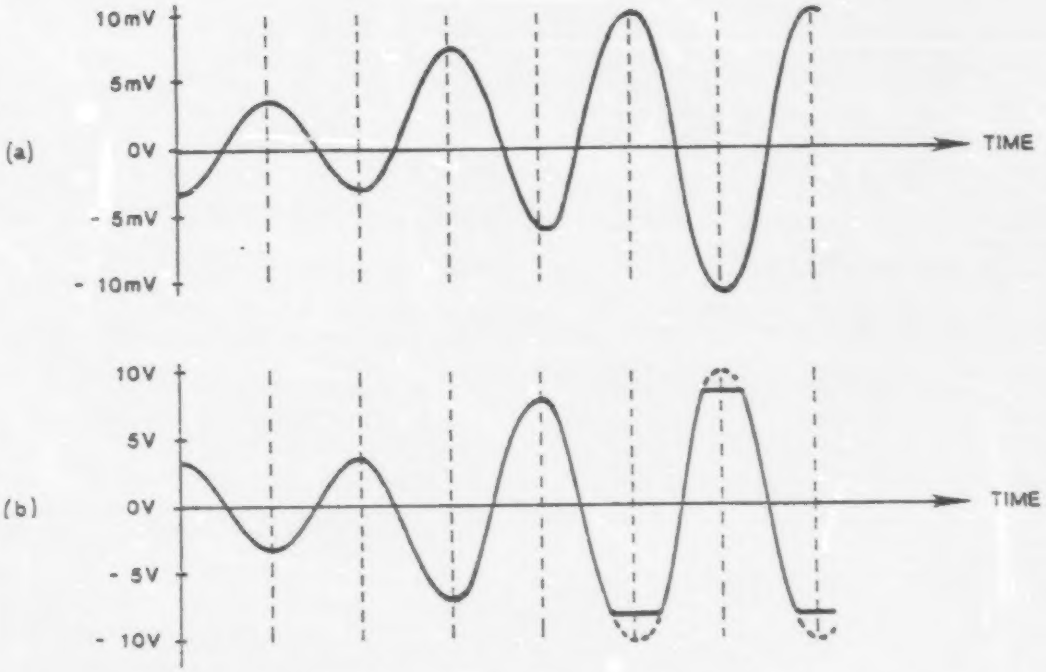

Figure 34-5-5. Input and output voltage of op amp.

When the input signal (Figure 34-5-5a) swings positive and negative, it is amplified and reproduced on the output. The output voltage is a replica of the input until the voltage level approaches the power supply level, at which time it is clipped. Figure 34-5-5b depicts the output that corresponds to the input. The output is clipped at these points at about 8 volts. The output should have gone to 10 volts. A_{VOL} = 1000, and V_o = 100 V_{in}.

As indicated by Figure 34-5-5, which presents the input and output waveforms for the op amp in Figure 34-5-4, the output follows the input until V_o = 8 V. The dotted lines indicate what the output level would have been for true representation.

As the input was connected to the inverting input of the amplifier, the output is inverted from the input. This simply means that, as the input signal was increasing in amplitude, the output level was decreasing, causing a phase shift of 180°. Waveforms for the noninverting amplifier in Figure 34-5-6 are illustrated in Figure 34-5-7.

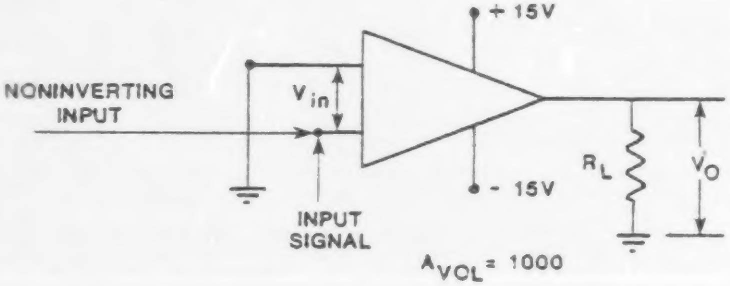

Figure 34-5-6. A noninverting op amp without feedback. A_{VOL} = 1000.

The waveforms in Figure 34-5-7 indicate no phase shift between input and output voltage because the input signal was applied to the noninverting input. The choice of which input connection to use is a decision made by a circuit designer and depends upon the desirability of the

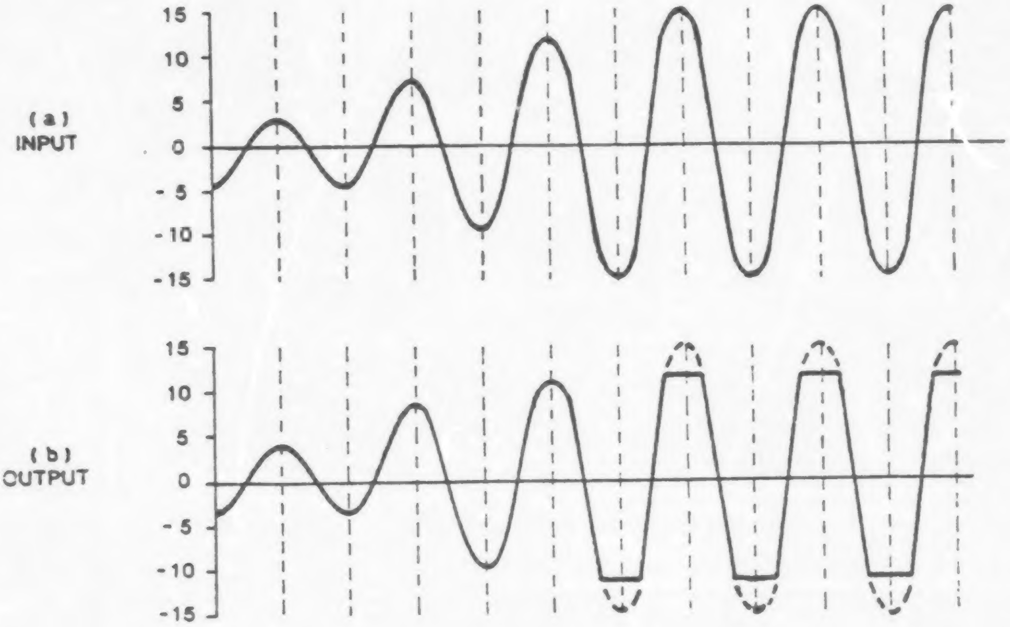

Figure 34-5-7. Input and noninverting output of an op amp.

phase relationship between input and output. The output signal level in Figure 34-5-7 is higher before clipping occurs because of the greater power supply voltage. The power supply voltage is governed by the op amp characteristics and is listed in the manufacturer's specification sheets. Some op amps have very high power supply voltage levels on the order of 100 V, and output voltage levels can approach that voltage magnitude. Clipping occurs at approximately 12 V. The output would have gone to 15 volts. $V_O = V_i$ (gain) = $(15 \times 10^{-3})(1000)$ = 15 volts.

NEGATIVE FEEDBACK AND THE INVERTING AMPLIFIER

Negative feedback occurs when a portion of the output signal is applied or fed back into the input at any point at which the input and output signals are out of phase, as was demonstrated in Figures 34-5-4 and 34-5-5. The op amp circuit in Figure 34-5-8 has negative feedback because the input is connected to the inverting input connection and because the output is connected through a resistor to the inverting input connection.

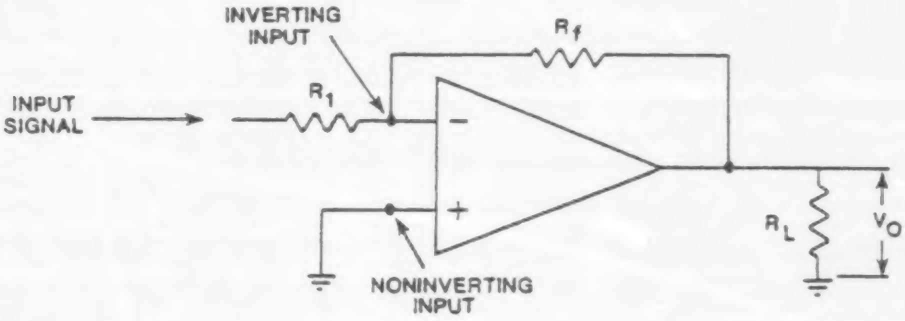

Figure 34-5-8. An inverting op amp with negative feedback.

The feedback resistor R_f connects the output – which is inverted, or moving in an opposite direction to the input – to the inverting input terminal. This allows a portion of the amplifier's output to be connected to the input. This negative feedback relationship reduces the gain of the amplifier below A_{VOL}, the open-loop gain. The amplifier gain with negative feedback is the closed-loop gain because the feedback resistor R_f completes a loop from the amplifier's output to the inverting input. The closed-loop gain A_V is determined by the ratio of the values of R_f and of the input resistor R_1, in accordance with Equation 34-5-3.

$$A_V = \frac{V_o}{V_i} \qquad \text{Eq. 34-5-3}$$

where:

A_V = closed-loop voltage gain.
V_o = output voltage.
V_i = input voltage.

FEEDBACK AND THE IDEAL AMPLIFIER

Because of the very high open-loop gain (A_{VOL}) of an op amp, the input voltage V_i to an op amp is very small, almost zero. Therefore, virtually no potential is developed across the input terminals; and with the noninverting input grounded (Figure 34-5-8), the inverting input is at virtual ground. From these conditions, the equivalent circuit of the inverting op amp with feedback is presented in Figure 34-5-9.

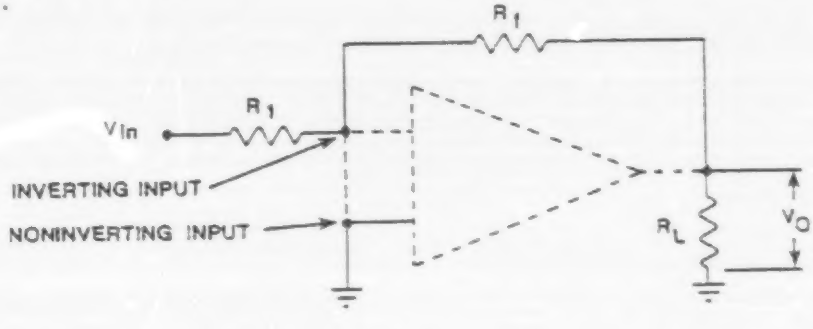

Figure 34-5-9. The equivalent circuit of the op amp in Figure 34-5-8.

With R_f connected to V_o on the right and to one side of R_1 on the left (which is at virtual ground), V_o dropped across R_f and $V_o \cong R_f I_f$. By the same reasoning, $V_i \cong R_1 I_1$. From Equation 34-5-3 –

$$A_V = \frac{V_o}{V_i}\ ,\ A_V = \frac{R_f I_f}{R_1 I_1} = -\ \frac{R_f}{R_1}.$$

For this to be true, I_f must be equal to I_1, which is an ideal op amp. Equation 34-5-4 gives the closed-loop gain of an op amp.

$$A_V = -\ \frac{R_f}{R_1} \qquad \text{Eq. 34-5-4}$$

where:

R_f = feedback resistor.

R_1 = input resistor.

The minus sign in Equation 34-5-4 indicates a phase shift between the input signals and output voltage.

In practical circuit design, R_f is not greater than 10 MΩ; and R_1, which is the load to the signal source, is 1 KΩ or greater. This is to avoid signal-source loading.

EXAMPLE

Given: $R_1 = 1\ K\Omega$; $R_f = 10\ M\Omega$.

Find: The closed-loop op amp gain.

Solution: Use Equation 34-5-4:

$$A_V = -\frac{R_f}{R_1}$$

$$= \frac{10 \times 10^6}{1 \times 10^3}$$

$$A_V = 10{,}000.$$

NOTE: In this Example and in the following one, the negative sign in Equation 34-5-4 did not enter into the calculations. A negative value for resistance or gain in this situation would have no significance. The negative sign specifies phase inversion.

EXAMPLE

Given: $R_1 = 4\ K\Omega$; $A_V = 3{,}000$.

Find: R_f.

Solution: Solve Equation 34-5-4 for R_f:

$$A_V = -\frac{R_f}{R_1}$$

$$R_f = A_V R_1$$

$$= (3{,}000)(4{,}000)$$

$$R_f = 12\ M\Omega.$$

FEEDBACK AND THE NONINVERTING AMPLIFIER

When the input signal is connected to the noninverting input, the op amp equivalent circuit is as depicted in Figure 34-5-10. The output voltage V_o is essentially equal to the input current times the sum of R_1 and R_f because R_1 and R_f are effectively in series. The input resistance at the junction point of the two resistors is very high. The output voltage V_o then can be determined as follows:

$$V_o = R_1 I + R_f I$$

$$V_o = (R_1 + R_f)\ I$$

With A_{VOL} being very large and the voltage drop between the two input connections being nearly zero, the input voltage is dropped across R_1; and $V_i = R_1 I_1$. Since –

$$A_V = \frac{V_o}{V_i} ,$$

and

$$\frac{V_o}{V_i} \cong \frac{(R_f + R_1)\ I}{R_1 I} = \frac{R_f + R_1}{R_1},$$

then

$$A_V = \frac{R_f + R_i}{R_i} = \frac{R_f}{R_i} + 1. \qquad \text{Eq. 34-5-5}$$

EXAMPLE

Given: The feedback resistor R_f of an op amp is 10 KΩ. The input resistor R_i is 1 KΩ.

Find: The voltage gain.

Solution:

$$A_V = \frac{R_f}{R_i} + 1$$

$$= \frac{10 \times 10^3}{1 \times 10^3} + 1$$

$$= 10 + 1$$

$$A_V = 11.$$

The gain of the amplifier in the foregoing Example is relatively low for op amps; however, the input resistance R_i would be very high. In some applications, the voltage gain is not as important as the op amp ability to match a source signal of high internal resistance to a low-resistance load. Op amps that perform such functions are known as "voltage followers," which now will be discussed.

OP AMP USED AS A VOLTAGE FOLLOWER

A voltage follower is a noninverting amplifier similar to the one depicted in Figure 34-5-6, where R_i is open and where R_f is shorted. For this configuration, $V_o = V_i$ since A_{VOL} is large; V_i is small; and the two inputs are virtually at the same potential. Figure 34-5-10 presents a voltage follower circuit. When the input and output signals nearly equal, the voltage gain of the voltage follower follows the input. As the closed-loop gain $A_V \cong 1$, the loop gain $A_{VOL}/A_V \cong$

A_{VOL}, which is very high. For this reason, the input impedance is very high. The effective output resistance can be decreased by reduction of the closed-loop gain.

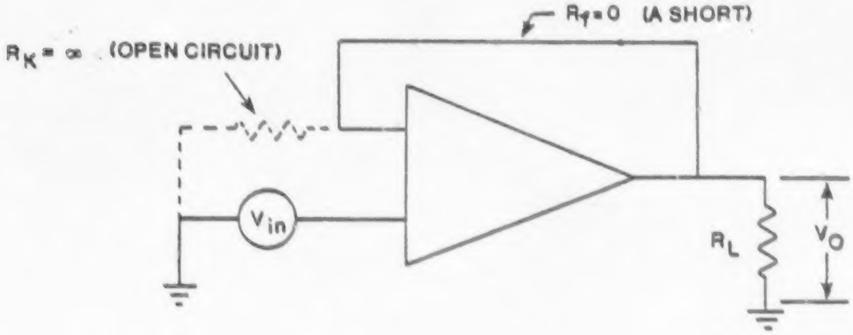

Figure 34-5-10. An op amp connected as a voltage follower.

OFFSET ADJUSTMENTS FOR BALANCED CONDITIONS

The ideal op amp will generate a voltage at the output terminal when the two inputs are at the same voltage level or at ground potential. Most op amp applications require that the output be at zero when the input signals are at a reference level. In order that this initial null or unbalanced condition can be obtained, a small voltage must be applied to one of the input connections. To produce a zero offset voltage on the output V_{oo}, the input voltage V_{io} may need to be either positive or negative at one input with respect to the other input V_{oo} before nulling can be either positive or negative with respect to ground.

Offset adjustments are necessary because of the imbalances that occur in the op amp internal circuitry. These imbalances result from the slightly different collector currents of the transistors on the input stage. The small variations of current are present even when the bases of both transistors are connected to the same potential and result in a differential output voltage from the first or differential stage. This voltage, which may be very small, is amplified through stages and results in the offset voltage V_{OO}. (Refer to Figure 34-5-11.)

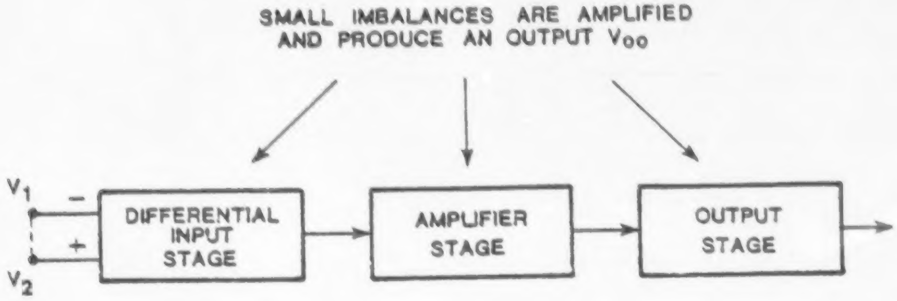

Figure 34-5-11. Imbalances in the input stage result in V_{OO} when $V_1 = V_2$.

The null balance circuits illustrated in Figure 34-5-12 drive V_{OO} to zero to establish the initial operating conditions for op amp applications. These circuits for inverting amplifiers can be used to null noninverting amplifiers when similar connections are made to the noninverting input. In each circuit, the POT on the input connection can be adjusted to provide a voltage of the exact magnitude and polarity required to balance the op amp. The circuit in Figure 34-5-13 displays external connections provided for null adjustment on many op amps.

Although the actual procedure used to balance an op amp may vary, depending upon the type and manufacturer, the general procedure is to connect both inputs to a ground potential and to adjust the POT connected to one of the inputs until the output is zero.

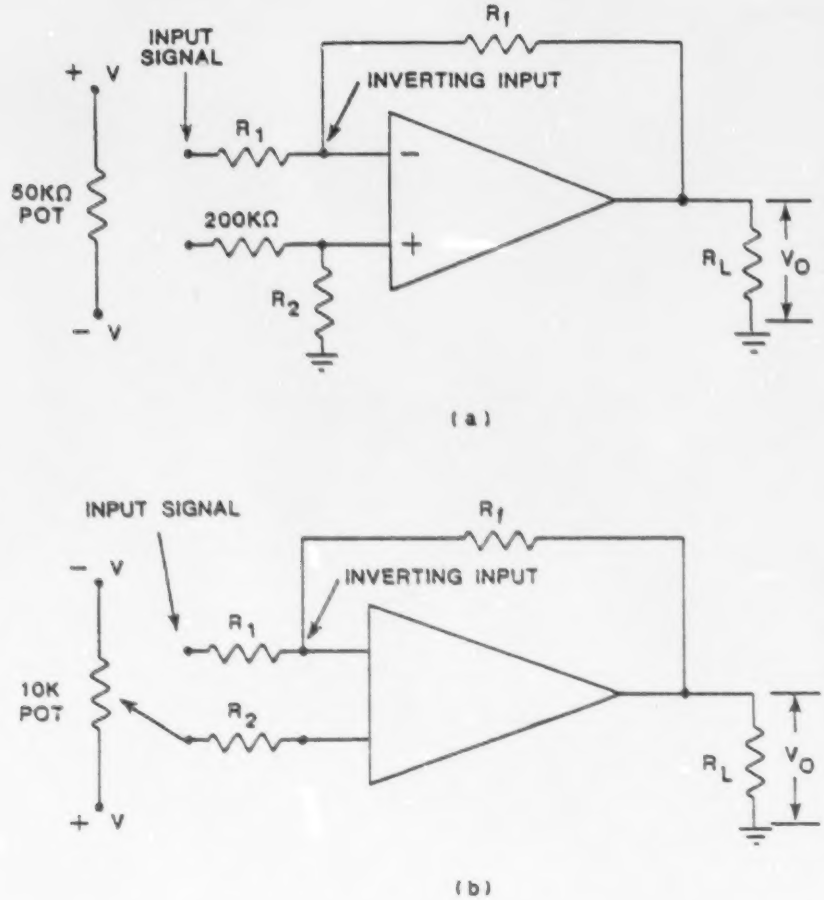
INPUT SIGNAL
R_f
INVERTING INPUT
+ V
R_1
50KΩ POT
200KΩ
R_2
R_L
V_O
− V
(a)
INPUT SIGNAL
R_f
− V
INVERTING INPUT
R_1
10K POT
R_2
R_L
V_O
+ V
(b)

Figure 34-5-12. Null balance circuits for inverting amplifiers.

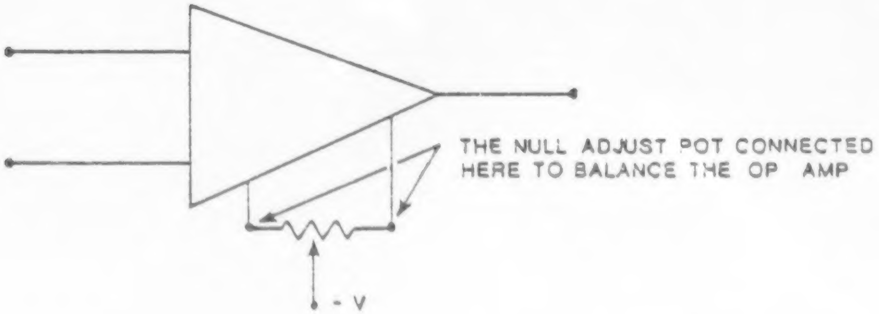
THE NULL ADJUST POT CONNECTED HERE TO BALANCE THE OP AMP
- V

Figure 34-5-13. External POT used to balance an op amp.

BIAS CURRENTS

The op amp, having transistors in the input stage, will require a bias current for the input. These currents will be small and about equal to each other. The input bias current can cause a problem by developing a potential difference between the two inputs (Figure 34-5-14). I_{B_1} sees some resistance when flowing to ground. I_{B_2} sees a short when flowing to ground.

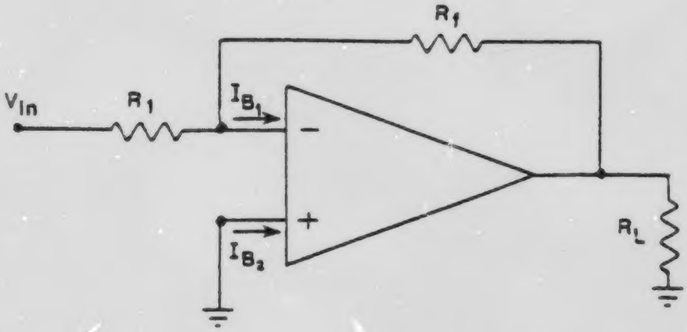

Figure 34-5-14. Difference in voltage at input caused by bias currents.

The amount of offset voltages caused by the two bias currents flowing to ground can be approximated from Equation 34-5-6.

$$V_{oo} = R_f I_B \qquad \text{Eq. 34-5-6}$$

where:

V_{oo} = offset output voltage.
R_f = feedback resistor.

$I_B \cong I_{B_1} \cong I_{B_2}$ which is the small input bias current specified by the manufacturer.

I_B is normally small (a few hundred nano amps); however, R_f can be large enough to make V_{oo} significant. To reduce V_{oo} caused by the input bias current, a value of R_2 equal to the resistance that I_{B_1} sees when flowing to ground is employed. When the two bias currents flow through resistances of equal value, the voltage on the input terminals caused by the currents will be equal. The circuit with the compensating resistor R_2 is presented in Figure 34-5-15. The value of R_2 is calculated from Equation 34-5-7.

$$R_2 = \frac{(R_1 + R_S)R_f}{R_1 + R_S + R_f} \qquad \text{Eq. 34-5-7}$$

where:

R_1 = input resistor.

R_f = feedback resistor.

R_S = resistance of the signal source; normally small and can be neglected.

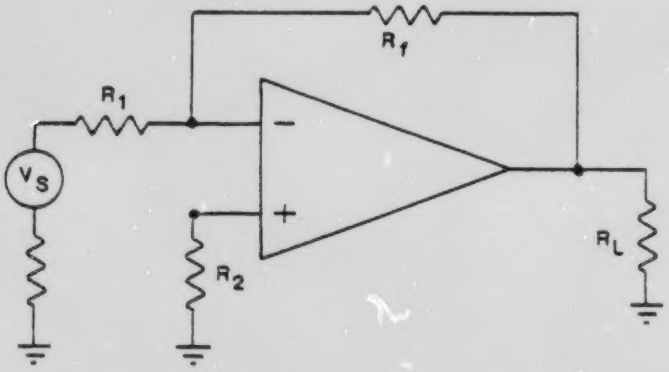

Figure 34-5-15. Resistor R_2 in series with the noninverting input to reduce V_{oo} caused by bias current I_B.

EXAMPLE

Given: $R_f = 0.5\ \text{M}\Omega$; $R_1 = 1\ \text{K}\Omega$; $R_s \cong 0\ \Omega$.

Find: The value of R_2 needed to reduce or to eliminate the output offset voltage.

Solution:

$$R_2 = \frac{(R_1 + R_s)\ R_f}{R_2 + R_s + R_f}$$

$$= \frac{(1\ \text{K}\Omega + 0\ \Omega)(0.5\ \text{M}\Omega)}{1\ \text{K}\Omega + 0.5\ \text{M}\Omega\ + 0\ \Omega}$$

$$= \frac{0.5 \times 10^9 \Omega}{0.501\ \text{M}\Omega}$$

$$R_2 = 0.998\ \text{M}\Omega.$$

The value of R_2 as calculated in the above Example will eliminate the offset voltage at the inputs when $I_{B_1} = I_{B_2}$. This is normally not a real case, however, and the addition of R_2 into the circuit under such circumstances will not completely eliminate the offset voltage. In such cases, V_{oo} normally can be driven to zero by the nulling circuit.

THE OP AMP AS A DIFFERENTIAL AMPLIFIER

When employed as a differential amplifier, the op amp produces a voltage output proportional to the difference in the voltage levels at the input terminals. The difference voltage to be amplified may be an a.c. voltage or a d.c. voltage. In certain applications, the signal voltage may be superimposed on another voltage level. When this occurs, the op amp must reject the common voltage applied to both inputs. Such rejection is termed "common mode rejection" and is a very important consideration in the design of op amp circuits. Error will be introduced into the measurement system if the output changes with variations in common-mode voltage.

Although an op amp is designed to reject common-mode voltage, some output common-mode voltage does exist. The ratio of the output common-mode voltage V_{cm} to the input common mode voltage V_i is called the "common-mode gain" (A_{cm}). The A_{cm} value usually is less than one for most commercial op amps. Most manufacturers do not list the A_{cm} value of their devices; instead, a common-mode rejection ratio is used. The common-mode rejection ration (CMRR) is the ratio of the change in V_{cm} to the resulting change in input offset voltage V_{io}. V_{io} is approximately equal to the ratio of the closed-loop gain A_V to the common-mode gain A_{cm}. These relationships are expressed by Equation 34-5-8.

$$\text{CMRR} = \frac{\Delta V_{cm}}{\Delta V_{io}} = \frac{A_V}{A_{cm}} \qquad \text{Eq. 34-5-8}$$

The maximum input voltage and common-mode voltage are listed on characteristic curves that relate the voltage limits to power supply voltage. These limits usually are a few volts below the power supply voltage.

OP AMP APPLICATIONS

A very common use of op amps in the nuclear industry is in the measurement of circuits. Wheatstone bridges are employed with transducers to detect changes in process variables. The change in variable imbalances the bridge circuit, and the bridge imbalance is detected and amplified to a usable signal level by an op amp. The circuit in Figure 34-5-16 can measure bridge imbalance caused by the transducer response, which represents process-variable changes such as temperature, pressure, fluid flow, and liquid level.

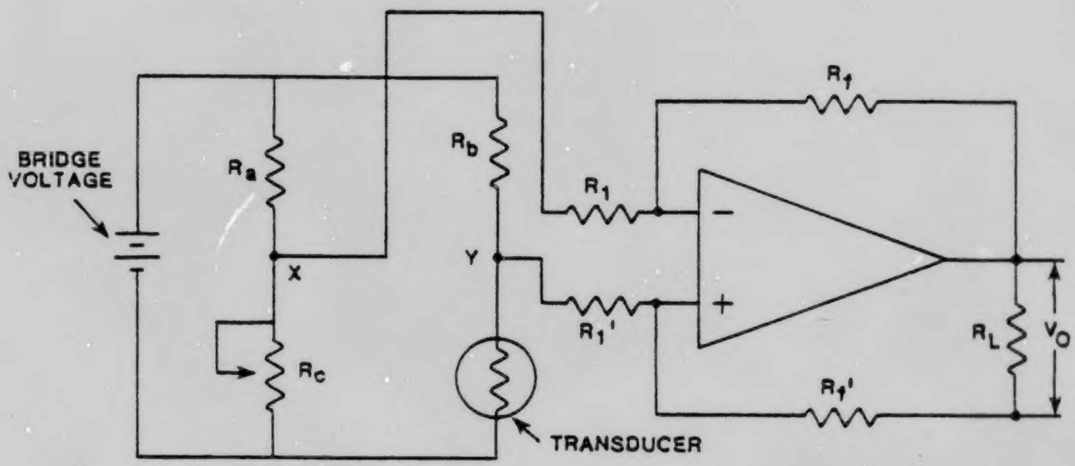

Figure 34-5-16. A bridge-measuring circuit driving an op amp. V_O is a function of the transducer variations.

The op amp input voltage V_i is the bridge imbalance voltage at points X and Y. The bridge sensitivity, in part, is a function of bridge voltage. When the bridge voltage is increased, the overall bridge sensitivity is increased; but this also increases the common-mode voltage on the op amp input terminals. The maximum bridge voltage is limited by the maximum common-mode voltage of the op amp. For good CMRR, $R_1 = R_1'$, $R_f = R_f'$, and $V_o/V_i = R_f/R$, although R_f and R_1 can be selected for the desired value of A_V. If

R_f and R_1 are selected for the A_V value, the load on the signal source will be changed; but this is not usually critical for most bridge applications. For cases in which signal-source loading is a consideration, voltage-follower stages can serve as a buffer between the signal source and the op amp input. Such applications are listed in the Reference Materials section of this module.

THE OP AMP AS AN INTEGRATOR

A very important use of integrator circuits in nuclear instrumentation applications is in electronic process controllers, where they provide a ramp output for the reset mode of control. This control mode sometimes is referred to as "integral" because of the integrator that provides the output.

The operation of an electronic integrator equipped with an op amp is clarified by the integrator circuit of Figure 34-5-17. With the noninverting input connected to ground, the inverting input is at virtual ground because of the zero potential assumed across the input. The input Voltage V_i appears across R_1, and the current through R_1 is indicated by Equation 34-5-9.

$$I = \frac{V_i}{R} \qquad \text{Eq. 34-5-9}$$

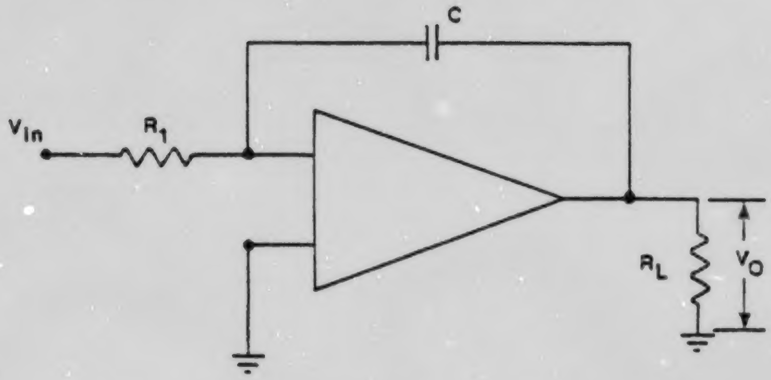

Figure 34-5-17. An op amp as an integrator.

The current I is forced through the capacitor because of the very high resistance at the inverting input. With the junction of R_1 and C virtually at ground potential, V_o appears across the capacitor as expressed in Equation 34-5-10.

$$V_o = \frac{1}{C}\int_o^t I_{dt} \qquad \text{Eq. 34-5-10}$$

where:

I = input current in the capacitor.

Since I = V_i/R by substitution into the above expression,

$$V_o = -\frac{1}{C}\int \frac{V_s}{R}\,dt = -\frac{1}{RC}\int V_s dt$$

EXAMPLE

Given: V_i = 1-volt step input at t_o; R = 1 MΩ;
C = 1 μfd.

Find: Output produced by the step input. Assume an ideal op amp and that initially C is unchanged.

Solution: By substitution into Equation 34-5-10 –

$$V_o = -\int 1\,dt$$
$$= -t + V_i$$
$$V_o = -t.$$

The output is a ramp function with negative slope when V_o is the output and V_i is the initial voltage on the capacitor or OV. There is a constant voltage on the integrator input.

$$V_{o(t)} = -t$$

and

$$V_{o(0.1\ sec)} = -t\ (0.1\,t) = -0.1t$$
$$V_{o(0.2\ sec)} = -t\ (0.2\,t) = -0.2t$$

A continuation of these calculations will demonstrate that the output is a ramp function with a negative slope increasing at a rate of 0.1t/sec. This proves the generation of a ramp function from an integrator.

THE OP AMP AS A DIFFERENTIATOR

When an op amp is utilized as a differentiator, the output is the derivative of the input. As indicated by Figure 34-5-18, the right side of the input capacitor C is virtually at ground potential; and the voltage across it is V_i. No current is flowing through the capacitor at static conditions. With a change in input voltage, a current I_c is flowing in the capacitor (Equation 34-5-11).

$$I_c = \frac{dV_i}{dt} \qquad \text{Eq. 34-5-11}$$

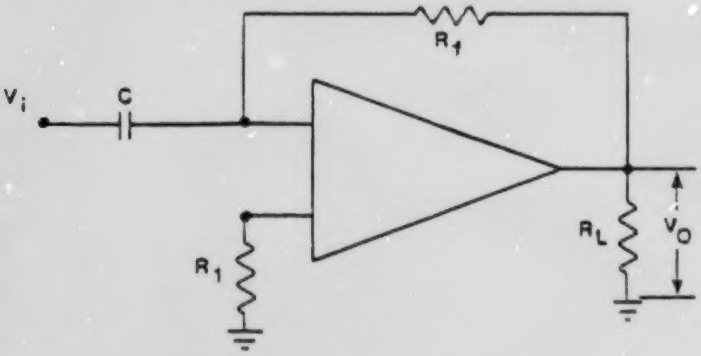

Figure 34-5-18. A basic op amp differentiator circuit.

This current is forced through the feedback resistor, which develops a voltage drop V_o across R_f.

$$V_o = R_f I \qquad \text{Eq. 34-5-12}$$

Equation 34-5-11 can be substituted into Equation 34-5-12 to solve for V_o as follows:

$$V_o = -R_f C \frac{dV_i}{dt} \qquad \text{Eq. 34-5-13}$$

The output voltage V_o then is the derivative of the input voltage V_i times the negative product of R_f and C.

The output of the differentiator responds to a change in the input waveform and is determined by the rate at which the change occurs. Because output is a function of the rate of change on the input, differentiators sometimes are called "rate circuits." The waveforms in Figure 34-5-19 indicate the input-output relationship of a differentiator. These circuits are used in process controllers for the rate, or

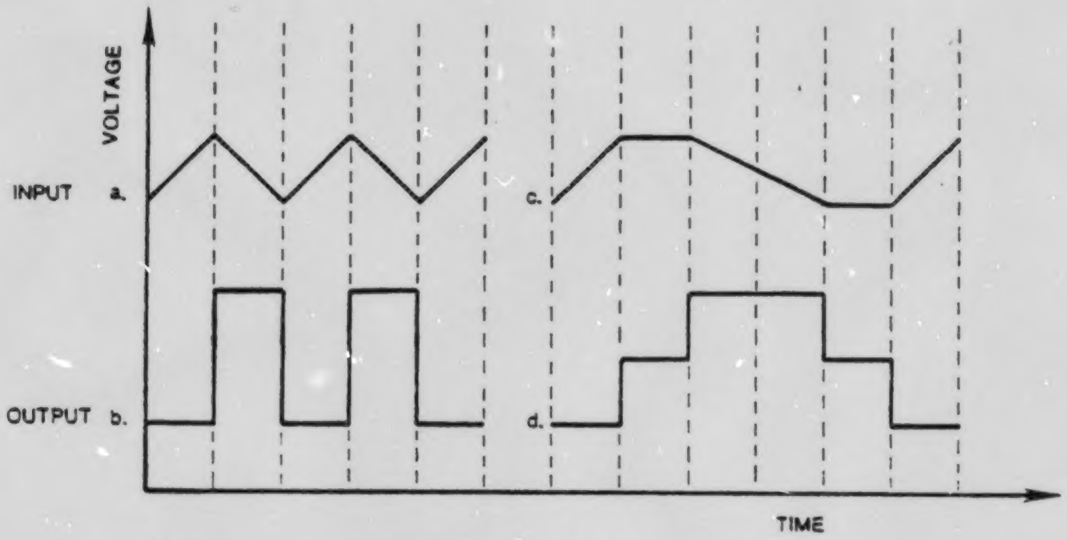

Figure 34-5-19. Differentiator input and output waveforms.

derivative, control mode, whose output is a function of the rate of change of deviation. The RC time constant in the feedback loop of the differentiator determines the amount of output generated for a given rate of change of the input signal.

Integrators and differentiators solve mathematical equations. On a larger scale, analog computers contain integrators, differentiators, and other components. A classic example of the use of integrators and differentiators is in the solving of equations that involve rate change of variables. The current flow with respect to time in a series RCL circuit is such an example. The circuit in Figure 34-5-20 is a block-diagram representation of the components needed to solve the following differential equation:

$$V = -L \frac{d^2Q}{dt^2} + R \frac{dQ}{dt} + \frac{Q}{C}$$

Or, solving for Q –

$$Q = LC \frac{d^2Q}{dt^2} - RC \frac{dQ}{dt} + CV_{in}.$$

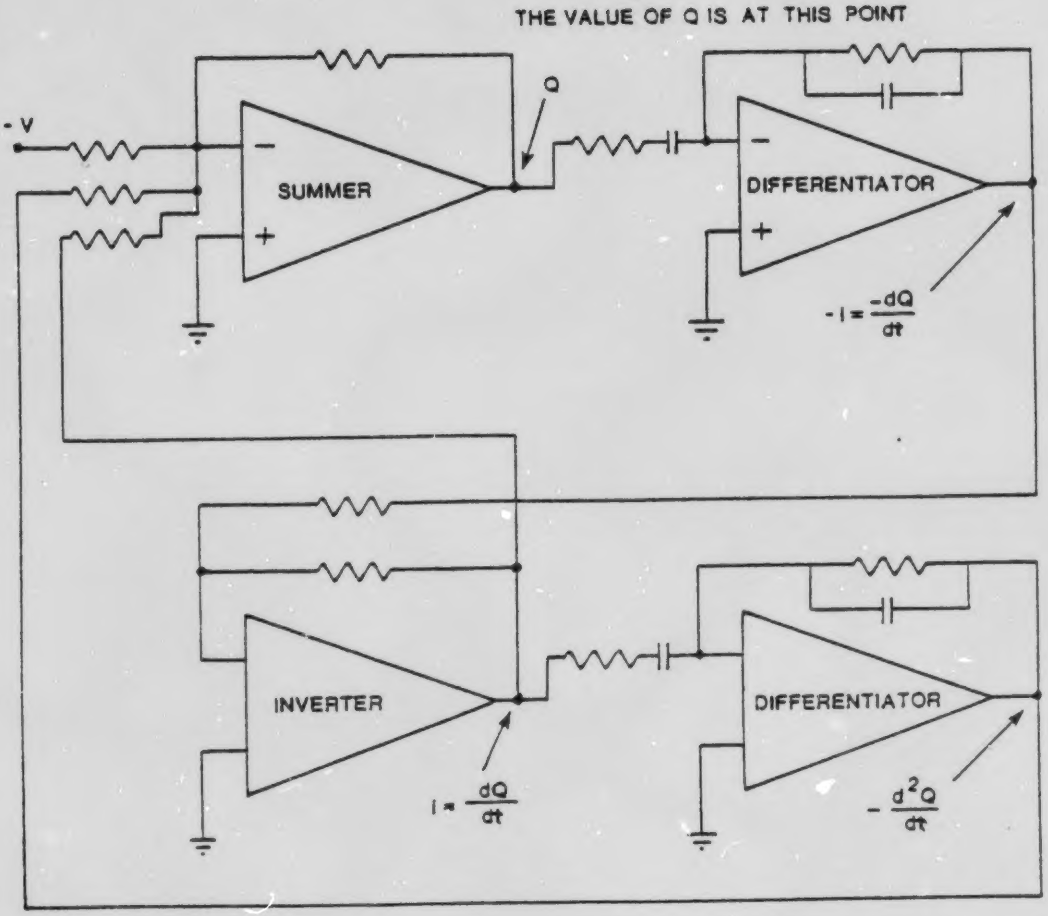
THE VALUE OF Q IS AT THIS POINT
Q
- V
SUMMER
DIFFERENTIATOR
$-I = \frac{-dQ}{dt}$
INVERTER
$I = \frac{dQ}{dt}$
DIFFERENTIATOR
$-\frac{d^2Q}{dt}$

Figure 34-5-20. Op amp used to solve a differential equation.

Figure 34-5-21 is the circuit for which the computations in Figure 34-5-2 were made. The value of V_{in} is given as —

$$V_{in} = -L \frac{d^2Q}{dt^2} + R \frac{dQ}{dt} + \frac{Q}{C}$$

Or, by rearranging and solving for Q —

$$Q = LC \frac{d^2Q}{dt^2} - RC \frac{dQ}{dt} + CV_{in}$$

A summer network can be set up to solve for Q — the input to each summer being one of the terms in the original equation above. The value of Q will be solved in microcoulombs and will be differentiated to obtain a current in microamps. This current will supply one of the inputs to the adder. The circuit can be used to examine current with respect to time (a nonlinear function) for a variety of input values. The value of Q is the charge on the capacitor and varies with the time to vary current.

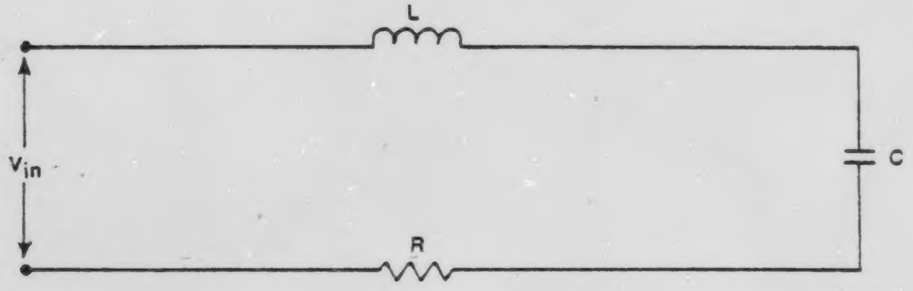

Figure 34-5-21. An RCL circuit provides the basis for calculations using op amp circuits.

OTHER OP AMP APPLICATIONS

Applications that involve the use of op amps are many in the instrumentation industry. Some important ones have been discussed in this module, but others equally important have been eliminated because of space required for explanation of a complete listing. The student is urged to seek the operating description and specific applications of the following op amp circuits listed in the Reference Materials section of this module.

- Square wave generators.
- Detector circuits:
    - Peak.
    - Peak to peak.
    - Phase.
- Comparators.
- Multivibrators.
- Logarithmic amplifier and other log circuits.
- Digital-to-analog converters.
- Voltage limiters.
- Power supplies.
- Schmitt trigger.

Many other op amp applications exist. Understanding will come with experience in dealing with these circuits.

EXERCISES

1. The steady-state voltage output of an op amp is 6 volts d.c., and overshoot response is 0.15 volts. Determine the percent of overshoot.
2. For an inverting amplifier for which R_f = 10 MΩ, R_i = 10 KΩ, and V_{in} = 0.2 microvolts, find V_o.
3. The input of a voltage follower is 1 mV. Find R_f, R_i, and A_V.

MATERIALS

Fairchild 741 op amp or equivalent.
An assortment of resistors with 1% tolerance.
+ 15-V power supply d.c. with regulation suitable for op amp operation.
Signal generator.
0-10 KΩ potentiometer, 1% tolerance.
A test instrument with 1 millivolt sensitivity.
A 14-pin, dual, in-line socket or breadboard such as the BL Instruments SK-10 socket.
Manufacturer's data or specification sheets.

PROCEDURES

PROCEDURE 1: COMPENSATING OFFSET VOLTAGE

1. Connect the circuit of Figure 34-5-22 in accordance with the pin connections listed in the manufacturer's data sheet.

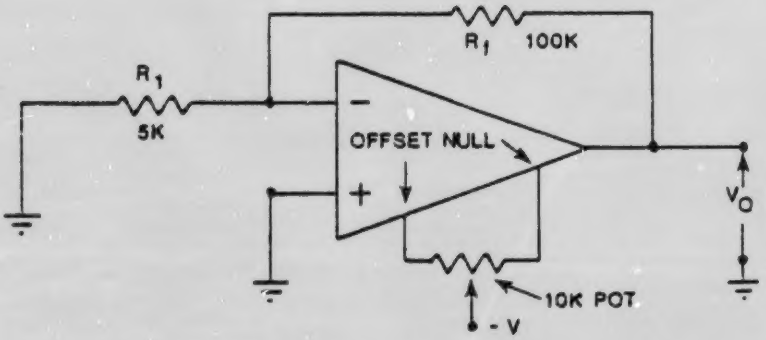

Figure 34-5-22. Experimental setup.

2. Turn on the power to the circuit; measure the output voltages; record this value as V_{oo} in Data Table 34-5-1.
3. Adjust the 10K POT until the output voltage as measured on the most sensitive scale of the test instrument is as close to zero as possible.
4. Calculate the closed-loop gain:

$$A_V = \frac{R_f + R_1}{R_1}$$

Record the value in Data Table 34-5-1.

PROCEDURE 2: INVERTING AMPLIFIER

1. Connect the op amp as in Figure 34-5-23, in accordance with the pin connections in the manufacturer's specifications. Leave the offset compensating POT in the circuit.

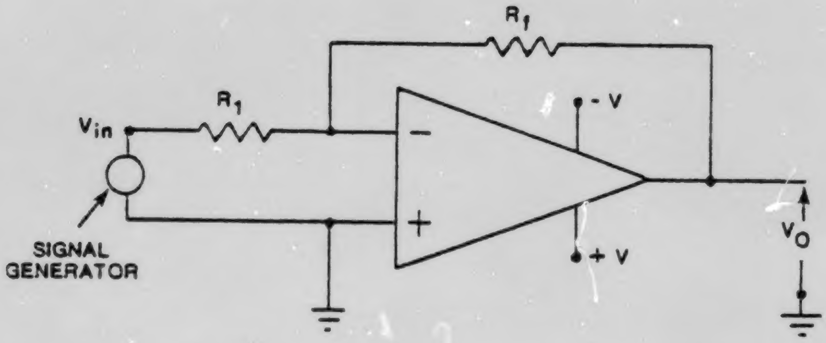

Figure 34-5-23. Inverting op amp.

2. With values of R_1 = 5 KΩ and R_f = 100 KΩ, calculate the amplifier gain; record the value in Data Table 34-5-1.
3. Turn on power to the circuit; and with a signal generator connected as in Figure 34-5-22, apply a small voltage while observing the output. When the output voltage reaches 0.5 V, measure V_{in}. Record the values in Data Table 34-5-1.
4. Slowly increase V_{in} until V_o increases 0.5 V. Measure V_{in}. Record V_{in} and V_o in Data Table 34-5-1.
5. Repeat Step 4 for a total of four values; record values in Data Table 34-5-1.

PROCEDURE 3: VOLTAGE FOLLOWER

1. Connect the op amp circuit as illustrated in Figure 34-5-24. Do not disconnect the offset voltage compensation.

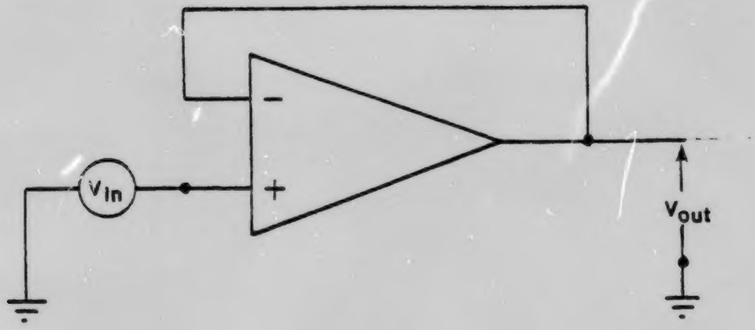

Figure 34-5-24. Voltage-follower circuit.

2. Apply 0.25 volts to the input. Measure and record the output voltage in Data Table 34-5-1.
3. Increase the input by one volt; measure and record the output voltage in Data Table 34-5-1.
4. Repeat Step 3 for a total of four readings.
5. Disconnect circuit.

PROCEDURE 4

1. Determine the measured value of A_V for each of the four entries in Procedures 2 and 3 of Data Table 34-5-1. Record these values in Data Table 34-5-1.

DATA TABLE

DATA TABLE 34-5-1

PROCEDURE I		PROCEDURE II				PROCEDURE III			
				A_V				A_V	
V_{oo}	A_V	V_{in}	V_o	M*	C	V_{in}	V_o	M	C

* M = measured value of A_V.
C = calculated value of A_V.

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Huelsman, Lawrence P.; Graeme, Jerald G.; Tobey, Gene E., eds. Operational Amplifiers. New York: McGraw-Hill Book Company, 1971.

Miller, Gary M. Linear Circuits for Electronic Technology. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1974.

Rutkowski, George B. Handbook of Integrated-Circuit Operational Amplifiers. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1975.

1. Define the following terms:
   a. Operational amplifier.

   b. Open-loop gain.

   c. Negative feedback.

   d. Inverting output.

   e. Noninverting output.

   f. Integrator.

g. Differentiator.

h. Common-mode rejection ratio.

2. Draw and explain the operation and possible use of
   a. An integrator.

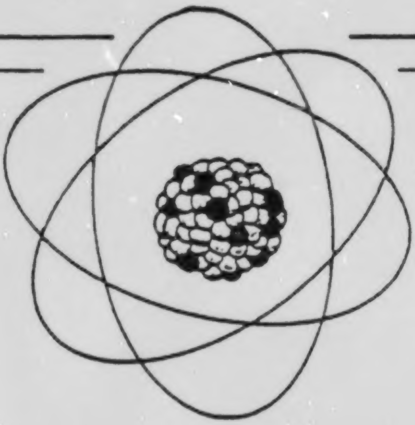
   b. A differentiator.

3. List a possible use of an integrator and differentiator in mathematical calculations.

4. The input to an op amp without feedback is 2 microvolts, and the output is 10 volts. Find the open-loop gain A_{VOL}.

5. The power supply voltage of the op amp in Test item 4 is 15 volts. What is the absolute maximum voltage available at the output?

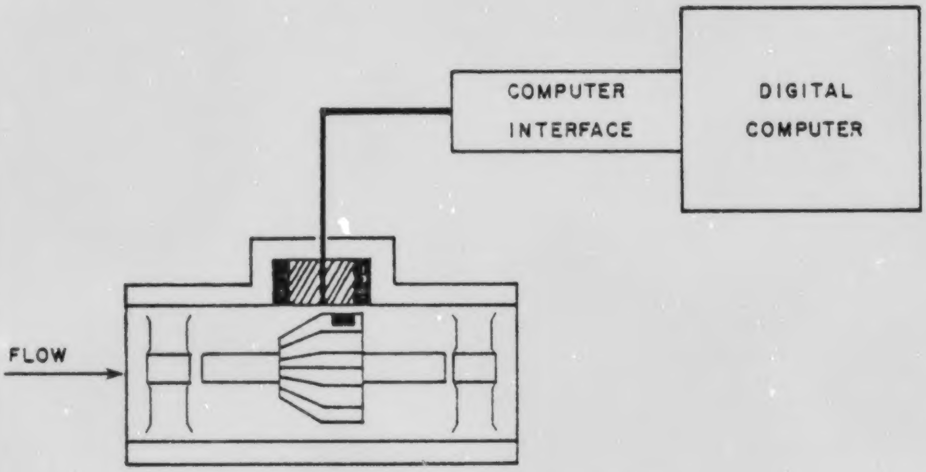
6. An op amp has an open-loop gain A_{VOL} of 10,000, and the power supply voltage is ±15 V. Determine the maximum input voltage that can be applied before clipping occurs, if the output is clipped at the power supply level.



NUCLEAR TECHNOLOGY

MODULE 34-6

MICROPROCESSOR UTILIZATION


COMPUTER
INTERFACE
DIGITAL
COMPUTER
FLOW

CONTROL SYSTEMS II
COURSE 34

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

COURSE MODULES

CONTENTS

COURSE 34 CONTROL SYSTEMS II

MODULE 34-1 Introduction to Transfer Functions
MODULE 34-2 Frequency Response Analysis
MODULE 34-3 Combination Control Systems
MODULE 34-4 Controller Tuning
MODULE 34-5 Operational Amplifiers
⇨ MODULE 34-6 Microprocessor Utilization
MODULE 34-7 Microprocessor Programming

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INTRODUCTION

The microprocessor is a miniaturized, low-cost computer that, typically, handles a wide variety of industrial and home applications. In the past, the microprocessor was a very primitive computer because it worked internally with 8-bit (called "byte") values and executed a relatively small number of machine operations (functions). Even today (1980), most microprocessors fit into this mold. Recently, however, microprocessors equipped with 16-bit, and even 32-bit, data paths have been introduced. The distinction between the microprocessor and its big-brother computers has shrunk to very little indeed. But for now, one can think of the microprocessor as just a very small computer.

Use of the microprocessor in nuclear power plants has been fairly recent. There has been some hesitation to allow the microprocessor into the nuclear field because of its relative newness and the question of its reliability compared to the larger main-frame computer and the mid-sized computer (minicomputer). However, over the last few years, the microprocessor has edged its way into almost every industrial area. Decreasing hardware costs and higher reliability have allowed the microprocessor to assume its place in nuclear power plants, especially in the newer ones.

This module introduces the use of microprocessors in the following areas of nuclear power plant operation and maintenance:

- Process and control systems.
- Radiation monitoring systems.
- Hardware diagnostics.
- Digital multimeters.

Programming is discussed in Module 34-7, "Microprocessor Programming."

MODULE PREREQUISITES

The student should have completed a course in Microcomputers; Course 3, "Principles of Process Instrumentation"; Course 6, "Instrumentation and Control of Reactors and Plant Systems"; Course 11, "Radiation Detection and Measurement"; Course 33, "Control Systems I"; and all previous modules of this Course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
    - Microcomputer.
    - PROM.
    - RAM.
    - Interface.
    - Peripheral.
    - Mask.
2. Explain and illustrate a microprocessor-based process control system and radiation monitoring system.
3. Describe the type of microprocessor utilized in each plant system.
4. List and discuss major peripheral microprocessor equipment.
5. Examine a process level channel using a microprocessor where typically analog signaling is utilized.
6. Discuss the limiting factors for use of a microprocessor in nuclear power plant safety-related protection channels.

DEFINITIONS

- Microcomputer – A computer whose capacity and capability is much smaller than a large computer's but which functions and manipulates data in a similar manner as its larger counterparts in performing initial data collection, computation, and storage in preparation for retrieval by the main computer. It usually consists of a memory, input/output (I/O), and other peripheral devices.
- PROM – Programmed read-only-memory, or memory that can be read only by the microprocessor in executing system programs but that is programmable by an outside device. EPROM, eraseable programmed ROM, is used for initial programming for ease of system program development, which requires numerous debugging exercises.
- RAM – Random access memory is that memory available to the microprocessor for storage of data randomly placed by the microprocessor for later retrieval for such executions as computational exercises.
- Interface – A point or device at which a transition between media, power levels, modes of operation, etc., is made.
- Peripheral – Having to do with a device by means of which a computer communicates to the outside world; includes such devices as magnetic tapes, discs, and drum memories.
- Mask – A logical technique in which certain bits of a word are blanked out or inhibited, based upon the interrupt signal received for execution of the interrupt operation required.

THE BASIC MICROPROCESSOR

Microprocessors provide an attractive alternative for, and increase capabilities to, the hardwired approach in process control systems. The digital approach provides several advantages over the analog approach, making possible —

- Increased precision because no accumulative errors occur as in analog loops (or channels). However, analog sensors and interfacing are the only limiting components.
- Increased flexibility of control systems by programming to desired application.
- Troubleshooting aid capability by incorporation of diagnostic programs that analyze hardware problems.
- Low cost.

However, the development or application of a microprocessor-based system requires detailed considerations for hardware selection and software programming to meet intended needs efficiently.

Usually, the microprocessor is an integral part of a basic system, or microcomputer, which includes peripheral components such as random access memories (RAM), read-only-memories (ROM), timers/counters, and power supplies. One microcomputer system is shown graphically in Figure 34-6-1. This system consists of the CPU, two 256-byte RAMs, one 1024-byte ROM, external clock input, and +5-volt power supply. The inputs and outputs are compatible with logic families such as TTL, CMOS, and low-power STTL. The ROM and RAM are N-channel memories that operate with any access time because of the asynchronous interfacing of this system. The I/O interface is also asynchronous, which enables the system to operate without buffers that provide external latching of data from these interfaces.

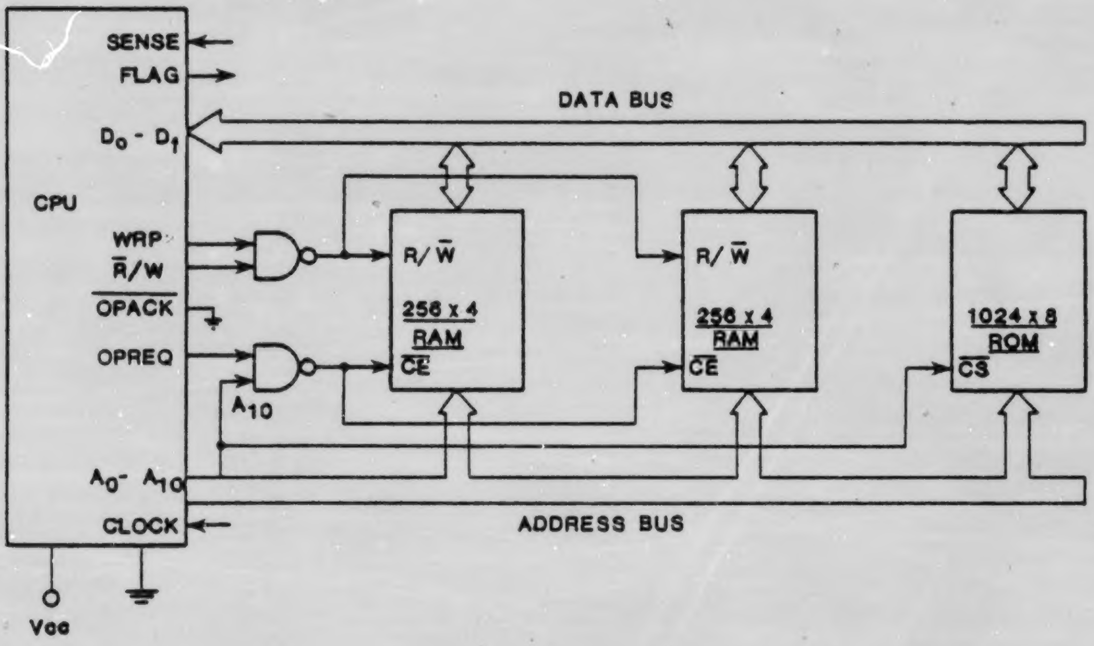

SENSE
FLAG
DATA BUS
D_0 - D_7
CPU
WRP
$\overline{R}$/W
$\overline{OPACK}$
OPREQ
A_{10}
A_0- A_{10}
CLOCK
ADDRESS BUS
Vcc
R/$\overline{W}$
256 x 4 RAM
$\overline{CE}$
R/$\overline{W}$
256 x 4 RAM
$\overline{CE}$
1024 x 8 ROM
$\overline{CS}$

Figure 34-6-1. Basic Microcomputer System (No. 1).

ROM in this system could contain a bootstrap loader and I/O driver programs for the I/O terminal. Other programs could reside in ROM or be written into RAM by use of the I/O terminal.

Signal codes are defined as follows:

- Sense – An input, independent of other I/O signals, that provides a direct input to the processor.
- Flag – A direct output from the processor; this output is completely independent of other I/O signals.
- D_0-D_7 – 8-bit, bidirectional, tri-state bus, over which most data is communicated into or out of the processor.

- WRP – Generated during write sequences and may be used to strobe memory or I/O devices.
- R/W – Output signal that describes an I/O or memory operation as READ or WRITE, and defines whether the bidirectional data bus (D_0-D_7) is transmitting or receiving.
- OPACK – Operation acknowledge input used by external devices to end an I/O or memory-signaling sequence.
- OPREQ – Operation request output informs external devices that the information on other outputs is valid.
- A_0-A_{12}– Low-order 13 bits of address for memory access where A_0-A_7 are also used in two-byte I/O instructions.
- CLOCK – Clock input to the processor; accepts standard TTL levels.
- VCC – +5-V power.
- GND – Logic and power supply ground for the processor.

The clock input provides the information required for the processor to perform its internal and external operations. The clock rate determines the instruction execution time, which depends upon the response of external memories and devices.

OPREQ is the master control signal that coordinates all operations external to the processor.

Another microcomputer system is illustrated in Figure 34-6-2. This system consists of the CPU, one 2k-byte ROM with two 8-bit I/O ports, and one integral 256-byte RAM and timer/counter with two 8-bit I/O ports and one 6-bit I/O port. Four interrupt levels and two serial I/O lines are provided at the CPU.

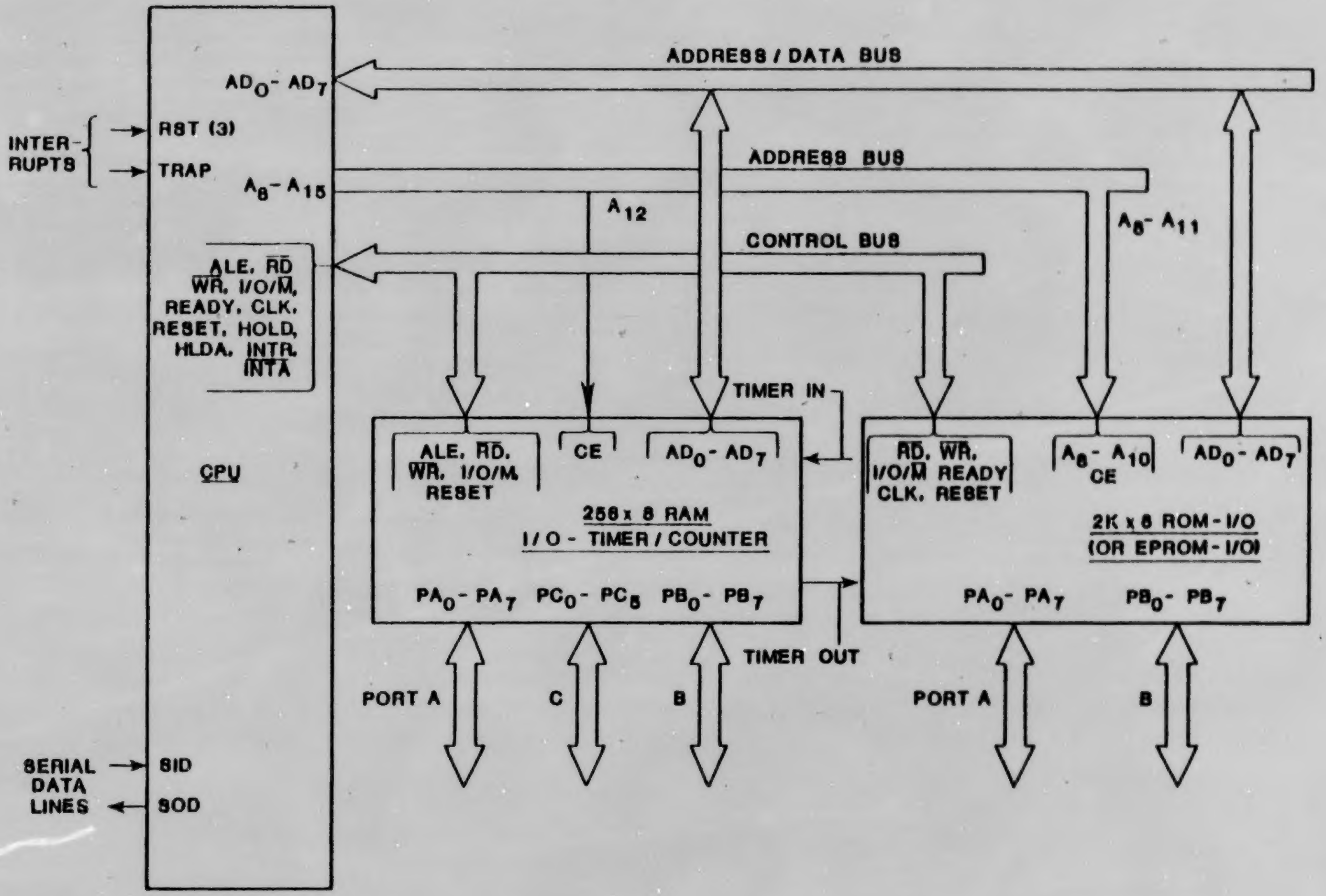

ADDRESS / DATA BUS
AD0 - AD7
INTER-RUPTS
RST (3)
TRAP
ADDRESS BUS
A8 - A15
A12
A8 - A11
CONTROL BUS
ALE, RD, WR, I/O/M, READY, CLK, RESET, HOLD, HLDA, INTR, INTA
CPU
TIMER IN
ALE, RD, WR, I/O/M, RESET
CE
AD0 - AD7
256 x 8 RAM
I/O - TIMER / COUNTER
PA0 - PA7
PC0 - PC5
PB0 - PB7
RD, WR, I/O/M READY CLK, RESET
A8 - A10
CE
AD0 - AD7
2K x 8 ROM-I/O
(OR EPROM-I/O)
PA0 - PA7
PB0 - PB7
TIMER OUT
PORT A
C
B
PORT A
B
SERIAL DATA LINES
SID
SOD

Figure 34-6-2. Basic microcomputer system (No. 2).

This system contains a component that combines memory, I/O, and timer functions and that provides for distributed task processing. This processing relieves the CPU of many of the bookkeeping, I/O, and timing tasks that usually are handled by system software. The CPU then concentrates on instruction execution, increasing the system speed.

Word system software development, an eraseable PROM, is utilized in place of the 2k-byte ROM. Such interchangeability allows development and debugging of software programs for final mask-programming of ROM.

Signal codes listed in Figure 34-6-2 follow closely to those of Figure 34-6-1 and are grouped into three categories – data/address, address, and control. They are defined as follows:

- Data/Address
  - AD_0-AD_7 – 8-bit, bidirectional, tri-state bus, which is time-multiplexed to transmit the eight lower-order address bits, as well.
- Address
  - A_8-A_{15} – 8-bit address bus, which, when combined with the lower-order 8 bits, AD_0-AD_7, provides a memory-addressing capability of 16 bits, allowing 64 k-bytes of memory to be accessed directly from the CPU.
- Control
  - ALE – A signal that indicates that the multiplexed bus contains the lower 8 bits of the address.
  - RD – A signal that identifies the READ operation and timing cycle of data transfer.
  - WR – A signal that identifies the WRITE operation and timing cycle of data transfer.

I/O/M – A signal that identifies a data transfer as being in the I/O address space or the memory address space.

READY, CLK
RESET, HOLD
HOLDA, INTR – These signals provide for synchronization of slow-speed memories, system reset, direct memory access, system timing, and CPU interrupt.

INTA – A signal that identifies the interrupt operation and timing cycle of data transfer.

SID,SOD – Input/output port, which provides for interface to a serial port in small systems that utilize software for timing and decoding of data.

RST – A maskable interrupt externally initiated for execution.

TRAP – A non-maskable interrupt that triggers the processor's hardware-interrupt sequence after internal acknowledgment of the interrupt signal.

MICROPROCESSOR-BASED SYSTEMS

With the advent of microprocessors, instrumentation systems have attained more versatility, flexibility, and capability than their analog counterparts. However, the use of a microprocessor-based instrumentation system must be thoroughly evaluated for each particular application. For example, nuclear power plants operate with two types of instrumentation systems – non-safety-related and safety-related. Safety-related instrumentation systems are required to operate with greater accuracy and speed that the non-safety-related system because of the protection-actuation function of this system. In addition, safety-related channels are required to be separated from the point of process measurement to the final actuator. In safety-related systems/channels, therefore, utilization of a microprocessor would be extremely costly and would degrade the overall response of the protection channel.

Microprocessors are utilized in two definite arrangements in process control systems: (1) analog process measurement and control of the final actuator with digital signal condition or manipulation and (2) all digital arrangements from the process measurement to the control of the final actuator. The all-digital system provides advantages over a hybrid system because it requires no signal conversions (D/As) where accuracy and response are affected and provides reliable, consistent, process signals where analog signals tend to drift, necessitating frequent calibrations or functional tests.

PROCESS CONTROL SYSTEMS

Figure 34-6-3 illustrates a typical pressurizer pressure-control system utilized on PWR systems at nuclear power plants. All phases in this control channel are analog signals. Since this channel is utilized for non-safety-related purposes, it is a prime candidate for implementation of the microprocessors.

A functional description of this channel is given in Module 35-2, "Instrumentation and Control for Nuclear Power Plant Components." However, the following brief description

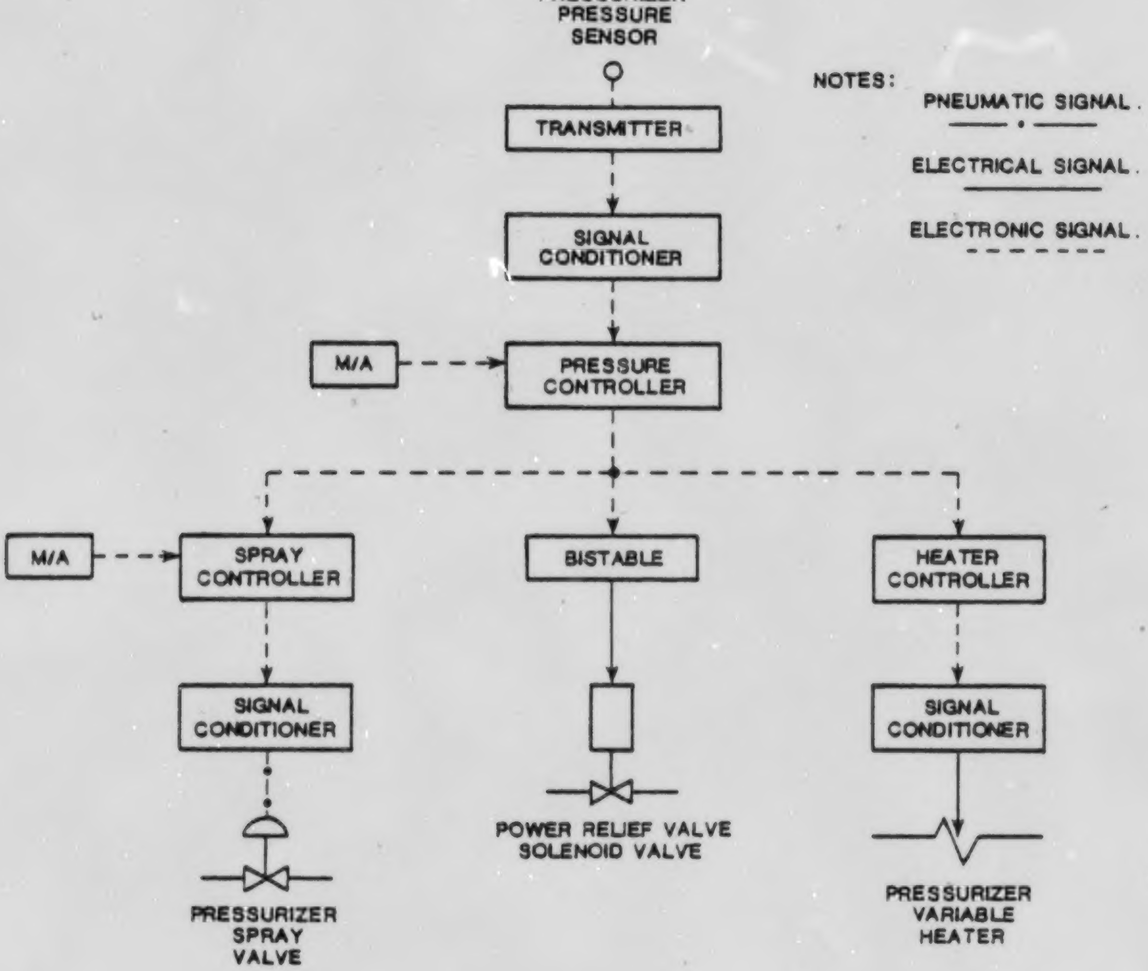

PRESSURIZER PRESSURE SENSOR
NOTES:
PNEUMATIC SIGNAL.
ELECTRICAL SIGNAL.
ELECTRONIC SIGNAL.
TRANSMITTER
SIGNAL CONDITIONER
M/A
PRESSURE CONTROLLER
M/A
SPRAY CONTROLLER
BISTABLE
HEATER CONTROLLER
SIGNAL CONDITIONER
SIGNAL CONDITIONER
POWER RELIEF VALVE SOLENOID VALVE
PRESSURIZER SPRAY VALVE
PRESSURIZER VARIABLE HEATER

Figure 34-6-3. Pressurizer pressure-control system.

of each equipment module explains the application of the microprocessor in this control scheme.

In the control channel of Figure 34-6-3, pressurizer pressure is sensed, converted to an analog current signal, signal conditioned, and provided as one input into the pressure controller. The controller possesses PID characteristics and compares the pressure signal to a reference signal in order to produce a proportional, time-response, pressure-deviation signal. The deviation signal then is utilized for proportional control of the pressurizer spray valve by the spray controller; of the power relief valve (solenoid valve) actuation, by the bistable; and of the pressurizer variable heater, by the heater controller. Manual/auto (M/A) control is provided for the pressure and spray controllers.

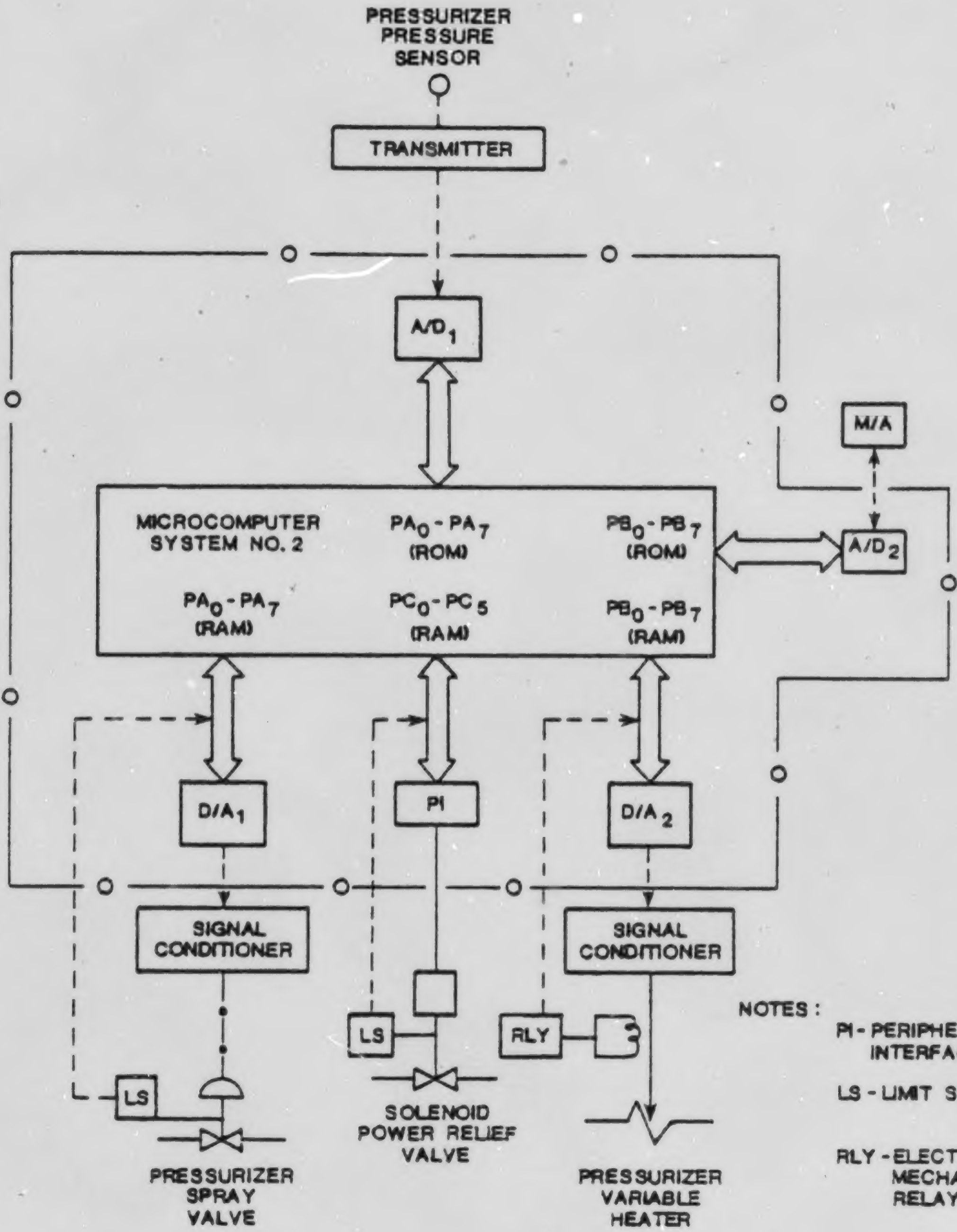
When the pressure controller is in auto, the actual pressure is compared to a pressure setpoint or reference to produce the proportional, timed-response, pressure-deviation signal. When in manual, the controller provides a deviation signal selected manually and has no derivative (rate) characteristics.

While in auto, the spray controller adds gain to the pressure-deviation signal from the pressure controller. In manual, the controller output no longer is based upon the deviation signal but upon the manual setting selected.

The heater controller only gains the deviation signal as required for proper control of the heaters, but the bistable actuates at a given deviation setpoint.

Figure 34-6-4 functionally illustrates the use of the basic microcomputer system of Figure 34-6-2. The microcomputer system and associated peripherals provide for over one-half the function of the analog modules.

In this system, the transmitter analog signal is converted to a digital signal by A/D_1 (analog-to-digital) converter. The output of the A/D_1 is an 8-bit parallel data stream stored in ROM. Since the operating pressure is approximately constant from 0-100% power on a PWR, a program could


PRESSURIZER
PRESSURE
SENSOR
TRANSMITTER
A/D1
MICROCOMPUTER
SYSTEM NO. 2
PA0 - PA7
(ROM)
PB0 - PB7
(ROM)
PA0 - PA7
(RAM)
PC0 - PC5
(RAM)
PB0 - PB7
(RAM)
M/A
A/D2
D/A1
PI
D/A2
SIGNAL
CONDITIONER
SIGNAL
CONDITIONER
LS
LS
RLY
SOLENOID
POWER RELIEF
VALVE
PRESSURIZER
SPRAY
VALVE
PRESSURIZER
VARIABLE
HEATER

NOTES:

PI - PERIPHERAL INTERFACE.

LS - LIMIT SWITCH.

RLY - ELECTRO-MECHANICAL RELAY.

Figure 34-6-4. Pressurizer pressure microcomputer system.

be stored in ROM and executed by the microprocessor to compare this pressure data to a known gauge of temperature data. Any possible approach to saturation conditions in the reactor coolant system would be detected early and alarmed for operator corrective action.

The manual/auto (M/A) station also outputs an analog signal that in auto is a pressure setpoint. The signal is converted to a digital signal by A/D_2. This data, which is also stored in ROM, would output directly to the final actuating devices when the M/A station is in manual mode. When in the automatic mode of operation, the setpoint data is compared to the actual pressure. The microprocessor then would perform the same PID functions on the developed pressure error as previously accomplished by the pressure controller of Figure 34-6-3. The output would be the gained time-response data necessary for proper control of the final actuating devices. Although not illustrated, an additional M/A station would be necessary for manual control of the spray valve.

Digital data based upon microprocessor PID and calculation of reactor coolant saturation are converted to analog signals by D/A_1 and D/A_2, which then position and set the pressurizer spray valve and variable heaters, respectively. Data necessary for PID and saturation calculations is stored in RAM.

Since the power relief valve is opened at a specific overpressure condition, the microprocessor determines the time of actuation by comparing actual system pressure (stored in ROM) to the known pressure setpoint (also stored in ROM). When conditions exist such that actual system pressure equals the overpressure setpoint, the 6-bit parallel digital data is received by the peripheral interface for relay actuation and energization of the solenoid power-relief valve. However, when saturation conditions are approached, the microprocessor would prevent any manual opening of the power-relief valve.

The microprocessor in this control scheme has the additional function of performing the diagnostics. By initiation from the multi-function M/A stations, the microprocessor would perform the following diagnostics with the system in a constant operating state:

- Determine the power-spectral density of the inherent-noise signal obtained from the process sensor/transmitter to measure any sensor/transmitter degradation.
- Simulate system pressure conditions to sense a slight —
    - Opening of the pressurizer spray valve by limit-switch acutation.
    - Current flow that results from actuation of the relaty for the pressurizer-variable heater.
    - Opening of the solenoid power relief by limit-switch actuation.
- Note: Response times would also be measured for each actuation.

After completion of each measurement or actuation, the microprocessor would determine the magnitude of hardware degradation from the power-spectral density of the sensor/transmitter and response times of each actuation as compared to baseline data. The results would be stored in RAM and accessible for further analysis. Any extreme, degraded condition measured by the microprocessor is alarmed for immediate corrective action.

It must be noted that the actuation of the pressurizer spray valve, solenoid power relief valve, and pressuizer-variable heater would be so sudden that system conditions would essentially remain unchanged.

RADIATION MONITORING SYSTEMS

Conventional radiation monitoring systems are analog ones that (1) convert signal pulses from detectors (ion-chamber, scintillation, etc.) into analog signals and that (2) condition them to alarm, display, record, and control. A microprocessor-based system operates in conjunction with a microcomputer system to convert pulses from the detector signal into digital form and processes the data for local data storage, indication, and control. Each remote microcomputer system can handle more than one detector and stores the radiation data as well as calculated values (integrated, accumulative, averages, etc.) for retrieval by a main computer system. Such a system is illustrated in Figure 34-6-5. The main computer system is used to collect all data from each remote detector microcomputer system for report processing, display, alarm, and control at the plant control center. The data then is used by plant control operators and health-physicists for personnel protection, waste processing, and report generation in meeting regulatory requirements.

The remote radiation microcomputer system consists of components depicted in Figure 34-6-6. This system functions in a similar manner as that described for the basic microcomputer system No. 2 (Figure 34-6-2). Addressing and data are based upon 8 bits. However, with the use of the ALE signal, 16-bit addresses can be generated to increase the amount of memory accessible by the CPU. Both EPROM and RAM are accessed by a 16-bit address (A_0-A_{15}); however, RAM data can be written into, as well as read from, the CPU.

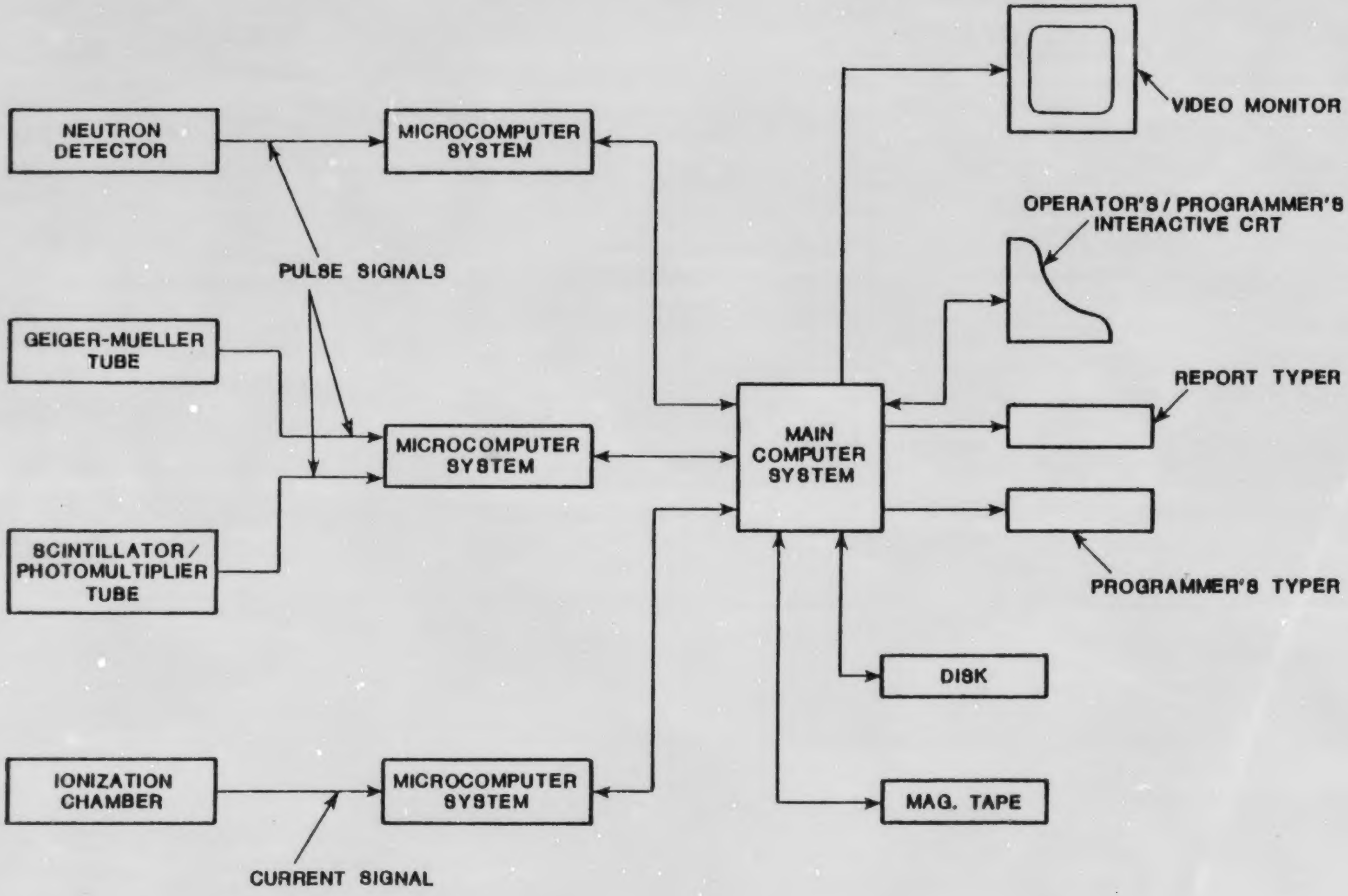
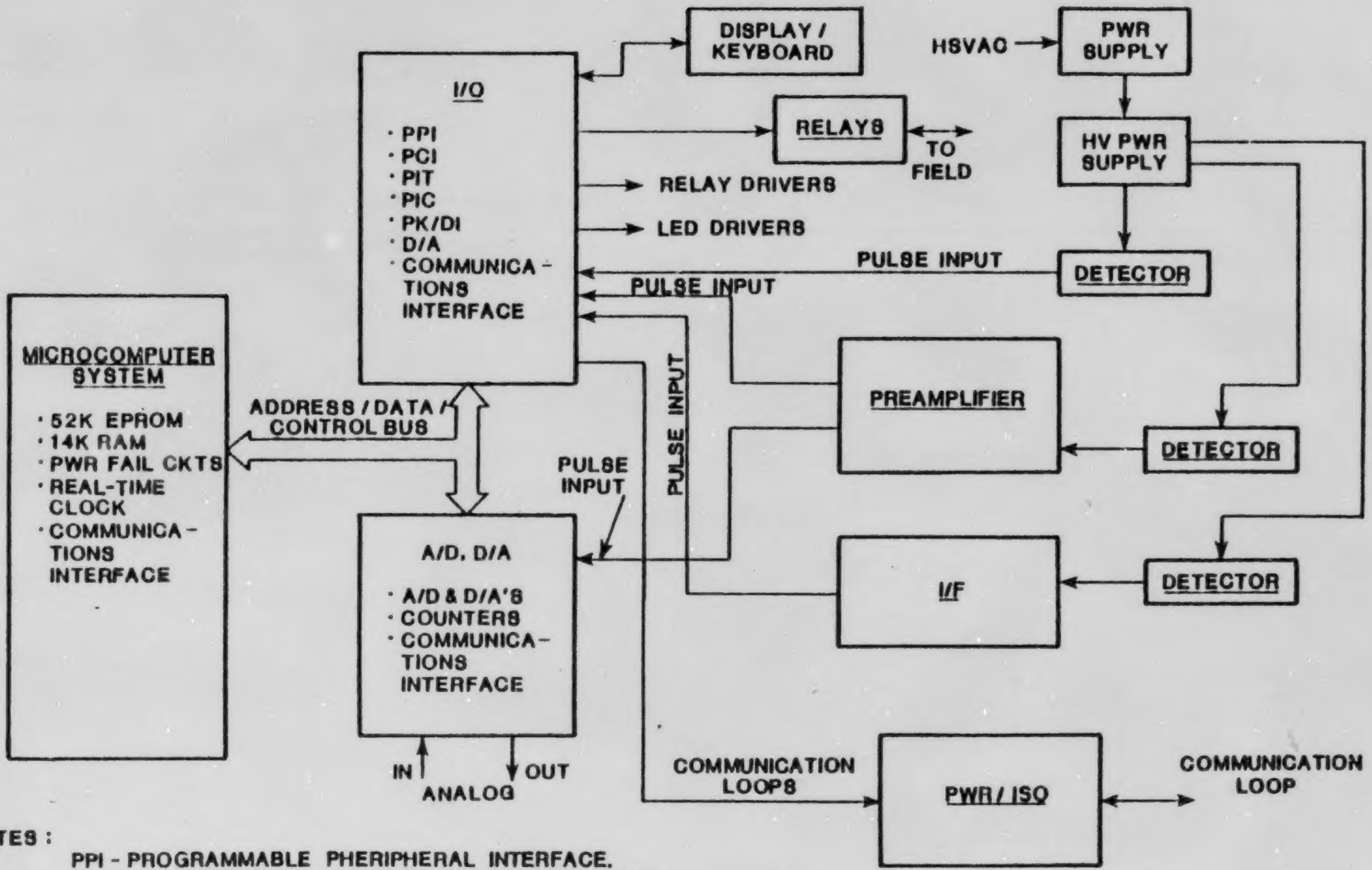

NEUTRON DETECTOR
MICROCOMPUTER SYSTEM
PULSE SIGNALS
GEIGER-MUELLER TUBE
MICROCOMPUTER SYSTEM
SCINTILLATOR/ PHOTOMULTIPLIER TUBE
IONIZATION CHAMBER
MICROCOMPUTER SYSTEM
CURRENT SIGNAL
MAIN COMPUTER SYSTEM
VIDEO MONITOR
OPERATOR'S / PROGRAMMER'S INTERACTIVE CRT
REPORT TYPER
PROGRAMMER'S TYPER
DISK
MAG. TAPE

Figure 34-6-5. Basic radiation monitoring system.


DISPLAY / KEYBOARD
HSVAC
PWR SUPPLY
I/O
• PPI
• PCI
• PIT
• PIC
• PK/DI
• D/A
• COMMUNICATIONS INTERFACE
RELAYS
TO FIELD
HV PWR SUPPLY
RELAY DRIVERS
LED DRIVERS
PULSE INPUT
DETECTOR
PULSE INPUT
MICROCOMPUTER SYSTEM
• 52K EPROM
• 14K RAM
• PWR FAIL CKTS
• REAL-TIME CLOCK
• COMMUNICATIONS INTERFACE
ADDRESS / DATA / CONTROL BUS
PREAMPLIFIER
PULSE INPUT
DETECTOR
PULSE INPUT
A/D, D/A
• A/D & D/A'S
• COUNTERS
• COMMUNICATIONS INTERFACE
I/F
DETECTOR
IN
ANALOG
OUT
COMMUNICATION LOOPS
PWR / ISO
COMMUNICATION LOOP

NOTES :

PPI - PROGRAMMABLE PHERIPHERAL INTERFACE.
PCI - PROGRAMMABLE COMMUNICATIONS INTERFACE.
PIT - PROGRAMMABLE INTERVAL TIMER.
PIC - PROGRAMMABLE INTERRUPT CONTROLLER.
PK/DI - PROGRAMMABLE KEYBOARD / DISPLAY INTERFACE.
I/F - CURRENT TO FREQUENCY.

Figure 34-6-6. Remote radiation microcomputer system.

The communications interface consists of data bus drivers that control the data bus between the CPU and the common data bus for associated peripheral components. When the CPU is addressing EPROM or RAM, the common data bus is inhibited from the CPU bus. When the CPU is reading or sending data on an I/O port, the CPU bus data is allowed on the common bus.

The use of other pertinent CPU signals are as follows:

- $I/O/\overline{M}$ – Determines whether the operation is to be an input/output operation or a memory operation.
- $\overline{RD}$ – Allows the CPU to read data from the data bus when the signal is low.
- $\overline{WR}$ – Signifies that the output data of the CPU is valid and can be accepted by other devices in the system when the signal is low.
- TRAP – Highest priority interrupt for power failure shutdown.
- RST – One RST is employed for real-time clock input. The other two RSTs are not used.
- INT – All communications interrupts developed on the I/O board are serviced through this input.
- RESET – CPU is reset to the address of the first instruction when the signal is low.

The I/O module consists of the following:

- Programmable Peripheral Interface (PPI). It handles the parallel multi-bit input and output data and is under direct control of the CPU.
- Programmable Communications Interface (PCI) consists of a synchronous/asynchronous receiver/

transmitter that converts parallel-format CPU data into serial format for transmission, and vice-versa for reception.

- Programmable Interval Timer (PIT). Modes of timing operation are adjustable through the use of several counters that are software programmable.
- Programmable Interrupt Controller (PIC). This unit handles vectored-priority interrupts for the CPU.
- Programmable Keyboard/Display Interface (PK/DI) provides control of display refresh and keyboard scanning.
- Digital-to-Analog Convertor (D/A). This unit is a converter whose output is amplified by an integrating amplifier to smooth the analog function for recording or for meter indication.

In addition, the I/O module accepts digital inputs utilized for addressing and diagnostic selection and nonisolated inputs that are TTL compatible. The digital inputs are received from three sources – a detector, a detector preamplifier, and an I/F converter. The detector preamplifier amplifies detector pulses when detectors are located several hundred feet from the microcomputer system, as is usually the case for process monitors. The I/F converter accepts an input current from a high-level gamma detector and converts the signal to a linear output frequency for processing by counters.

Finally, the I/O module contains (1) the communications interface for communicating with the microcomputer system, (2) relay driver outputs for control or testing purposes, (3) LED drivers for data display, and (4) a communications link to the main computer through the power/isolator module.

The A/D, D/A module provides the required interfacing with analog process signals. The process of an analog-to-digital conversion are performed for process signals as gaseous and liquid mass flow rates, pressure, and temperature. Digital-to-analog conversion is provided for remote analog recording of radiation data.

The power/isolator module provides the necessary isolation for, and driving current to, the communications link with the main computer. In addition, a power-failure circuit protects RAM memory in the microcomputer system for quick restart on restoration of power, and a watchdog timer resets the microcomputer system on a hardware failure or returns the system to a run condition after a power outage.

DIGITAL MULTIMETER

Microprocessor-based measuring and test equipment (M&TE), such as the digital multimeter (some types), is used in calibration or standard laboratories located at nuclear power plants. This equipment provides for additional capabilities, including (1) multiple measurements, calculations, and displays; (2) faster calibration of lower-tier M&TE through the use of data storage and programmability; and (3) easier integration with the IEEE-385 bus interfacing for calibration and automatic testing purposes.

Figure 34-6-7 is a block diagram of a digital multimeter (DMM) that utilizes a microcomputer system. The microcomputer controls data on the digital, analog, and input buses and prepares each analog module for a measurement by addressing the modules as memory locations.

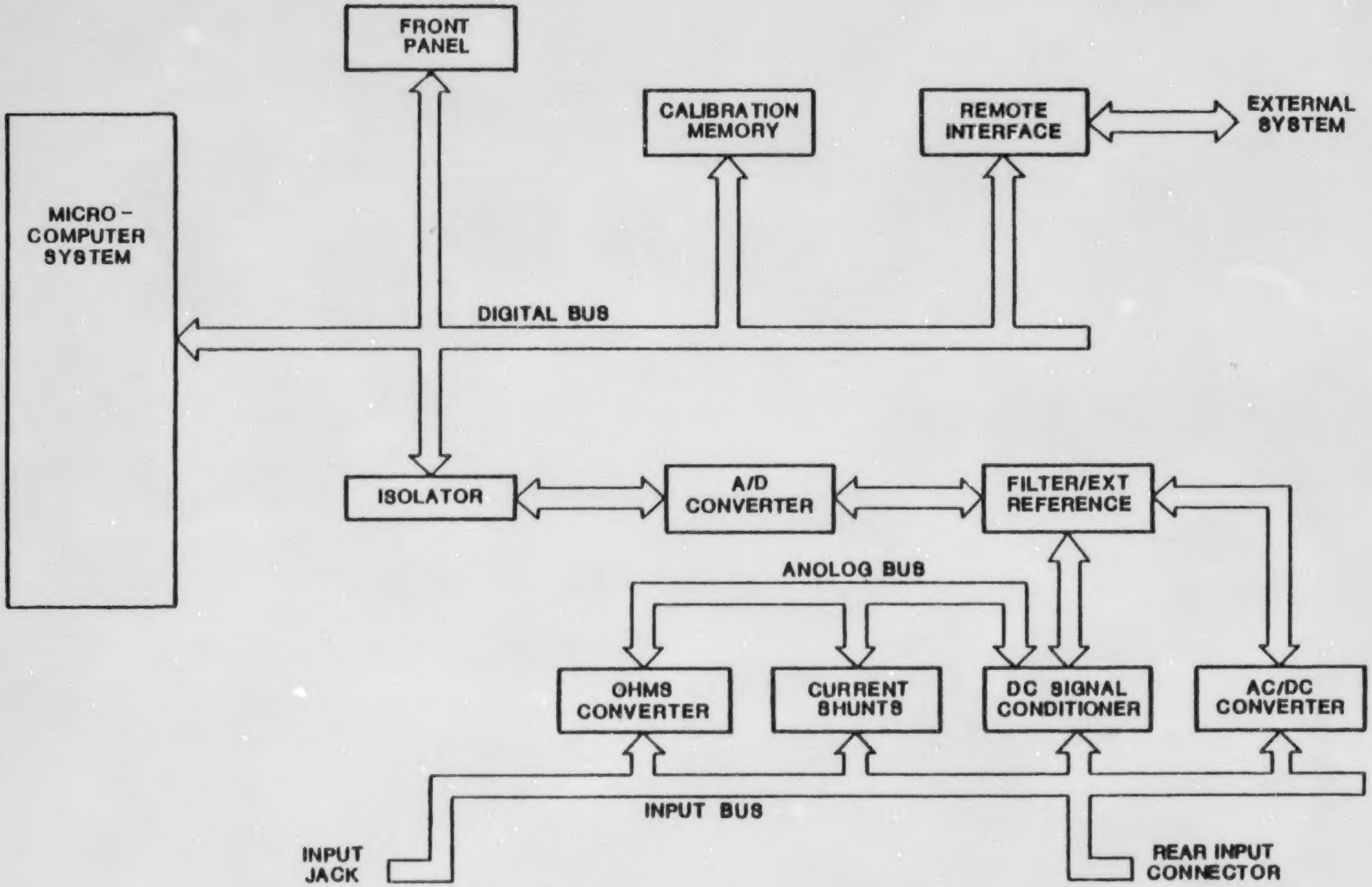

FRONT PANEL
CALIBRATION MEMORY
REMOTE INTERFACE
EXTERNAL SYSTEM
MICRO-COMPUTER SYSTEM
DIGITAL BUS
ISOLATOR
A/D CONVERTER
FILTER/EXT REFERENCE
ANOLOG BUS
OHMS CONVERTER
CURRENT SHUNTS
DC SIGNAL CONDITIONER
AC/DC CONVERTER
INPUT BUS
INPUT JACK
REAR INPUT CONNECTOR

Figure 34-6-7. Microprocessor-based DMM system.

The digital bus interties the microcomputer with the front panel; with calibration memory, which is used for short- or long-term storage of data; and with the remote interface, which is compatible with the IEEE-385 bus structure. It consists of control/address, bidirectional data, real time, and handshake (interrupt, acknowledge, interrupt acknowledge) lines.

The analog bus interties the microcomputer with the analog modules through an optical isolator used for protection. This bus consists of control/address, bidirectional data, real time, and the acknowledge handshake lines.

The input bus consists of lines that connect the analog input terminals to the signal conditioning and converting modules, which consist of the ohms, a.c./d.c., and A/D converters; the current shutns; and the d.c. signal conditioners.

The ohms converter provides the precision measurement of resistance, ranging from the hundreds of micro-ohms to the hundreds of megaohms. The a.c./d.c. converter converts a.c. signals (voltage and current) to d.c. levels that can be measured by the A/D converter. The A/D converter converts d.c. input signals into binary, bit-serial data streams for communication with the microcomputer, and vice versa. The current-shunts module generates a voltage proportional to the input current, and outputs either to the d.c. signal conditioner for d.c. currents or to the a.c./d.c. converter for a.c. currents. The d.c. signal conditioner converts d.c. signals from the ohms converter, current shunts (d.c. output), and d.c. inputs to a range acceptable to the A/D converter. Finally, the fitter/external reference multiplexes d.c. signals to the A/D converter and switches analog filters into the signal-conditioner inputs.

The microcomputer system illustrated in Figure 34-6-8, when operating a software program, addresses and initializes each module for performing a selected function. The program performs interrupt-drive activities such as updating the display digits; directing the A/D converters to sample data from the modules; and performing measurements, including the accumulation of data and performance of required calculations.

The sequence of events in the microcomputer system is timed by the microprocessor clock or generated by shaped line-frequency pulses. The frequency pulses are applied to a phase-locked loop that conditions the frequency signal used to generate mask interrupts.

Interrupts divert the microprocessor from the main program to service other routines and are synchronized, through interrupt control, to an appropriate time in the system cycle. The control module assigns priorities and places module identity data onto the data bus to direct the microprocessor to the memory location that contains the next instruction. The interrupt ACK INT is generated when an acknowledge signal is not received from an addressed module. The interrupt MARK INT synchronizes the line frequency for A/D sample data setting and display updating. In addition, interrupts can be generated externally by signalling of the INT input on the control module. When the microprocessor is ready to accept the interrupt, INA (interrupt acknowledge) will be generated.

System resets are generated by front panel or remote requests and occur at power up or power down, as well. Line-frequency pulses are sensed by the reset logic module to ensure that the system starts from the zero program location at power up and that the system will not address modules erroneously at power down.

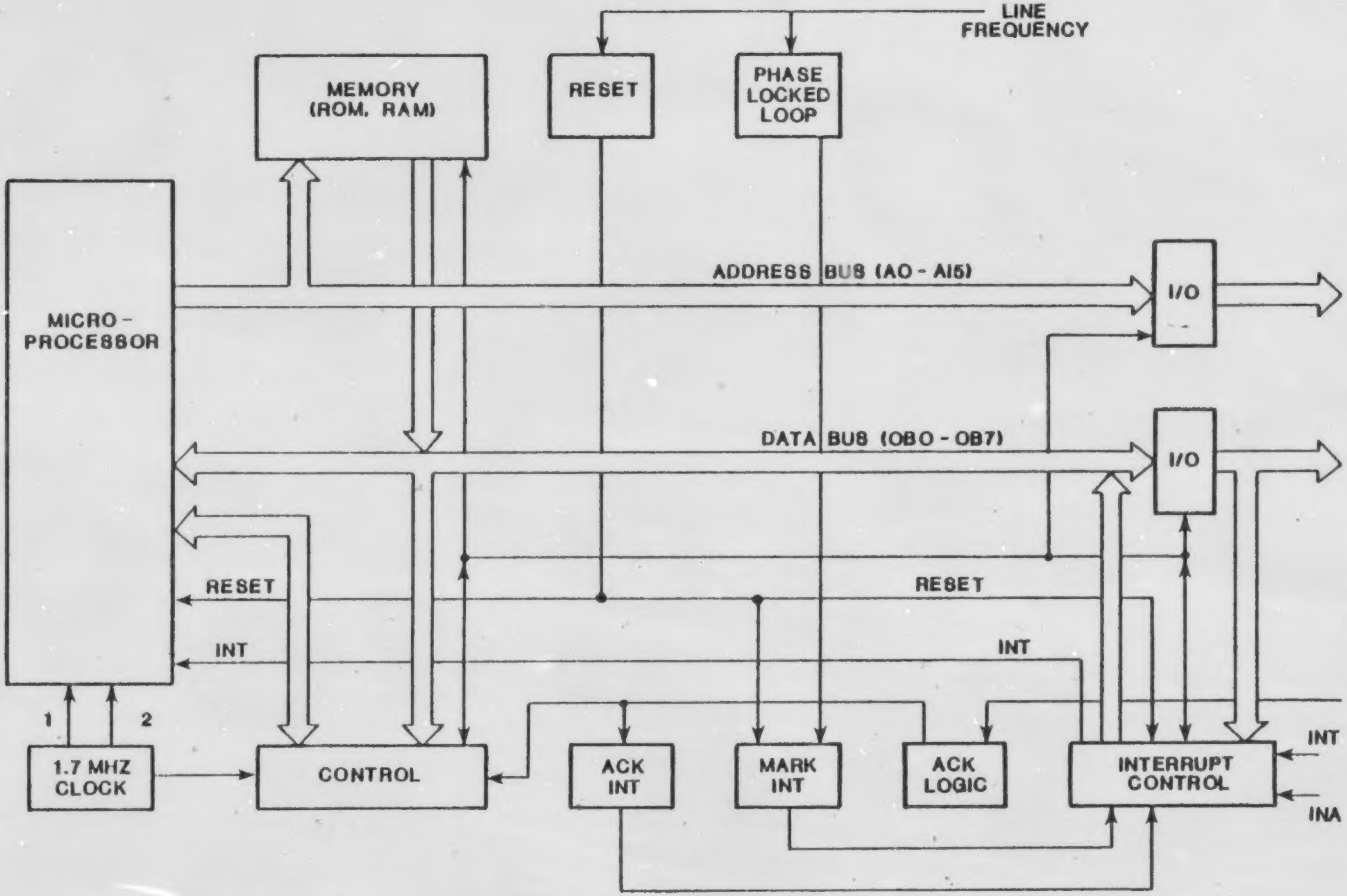

LINE FREQUENCY
MEMORY (ROM, RAM)
RESET
PHASE LOCKED LOOP
MICRO-PROCESSOR
ADDRESS BUS (AO - AI5)
I/O
DATA BUS (OBO - OB7)
I/O
RESET
RESET
INT
INT
1
2
1.7 MHZ CLOCK
CONTROL
ACK INT
MARK INT
ACK LOGIC
INTERRUPT CONTROL
INT
INA

Figure 34-6-8. A microcomputer system.

The control-logic module latches a status word at the beginning of each instruction cycle to control and synchronize data I/O, memory read/write, and some interrupt control signals. The module also instructs the microprocessor when to enter and to exit wait states. An instruction to enter a wait state is generated after an external module is addressed and after it is interrupted to allow the external module time to acknowledge.

System memory consists of both ROM and RAM storage. ROM stores operating-system and calculational programs and routines. RAM is used for temporary storage of microprocessor data.

EXERCISES

1. What considerations are involved in the development of a microprocessor-based process control system?
2. List the advantages and disadvantages of a microprocessor-based digital radiation monitoring system.
3. List the advantages and disadvantages of a microprocessor-based process control system in non-nuclear safety-related applications.

MATERIALS

None.

PROCEDURES

None.

DATA TABLE

None.

REFERENCE MATERIALS

Hall, Douglas V. *Microprocessors and Digital Systems*. New York: McGraw-Hill Book Company, 1980.

Harding, Bill. "*Valve Control with a Microcomputer*." Chilton's Instrument and Control Systems, Vol. 51, No. 10 (October, 1978).

Meggioli, Victor J. *Programmable Controllers in Process Control Applications*. IEEE Transactions on Industry Applications, Vol. IA-15, No. 6 (November/December, 1979).

MCS-85 User's Manual. Santa Clara, CA; Lutel Corporation, 1980.

Ogdin, Carol Anne. *Microcomputer Management and Programming*. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1980.

Siguetics Microprocessor 2650 – Introductory Brochure and Short Form Catalog. Sunnyvale, CA: Siguetics Corporation, 1980.

TEST

1. Define the following terms:
   a. Microcomputer.

   b. PROM.

   c. RAM.

   d. Interface.

   e. Peripheral.

   f. Mask.

2. Explain and illustrate a microprocessor-based process control system and radiation monitoring system.

3. Describe the type of microprocessor utilized in each plant system.

4. List and discuss the major peripheral microprocessor equipment.

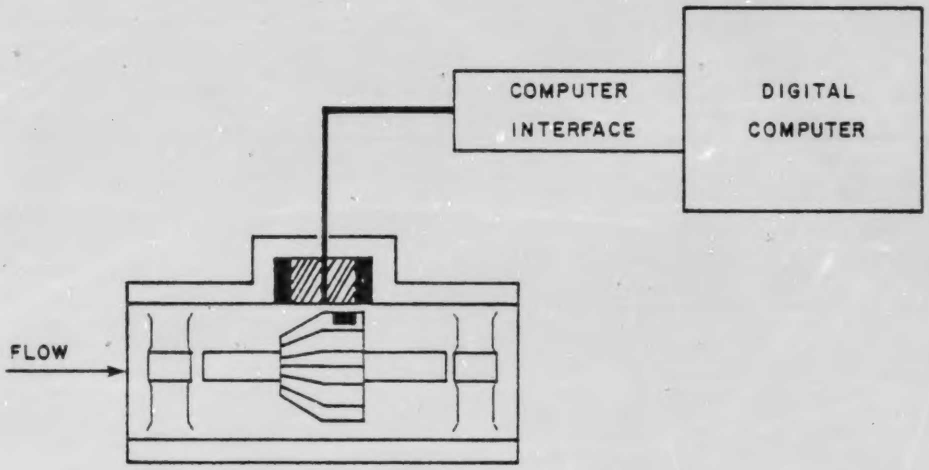
5. Why would digital signal processing be more accurate and reliable than analog signals?

6. What are the limiting factors for use of a microprocessor in nuclear power plant safety-related protection channels?

NUCLEAR TECHNOLOGY

MODULE 34-7

MICROPROCESSOR PROGRAMMING


COMPUTER INTERFACE
DIGITAL COMPUTER
FLOW

CONTROL SYSTEMS II
COURSE 34

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

COURSE MODULES

CONTENTS

COURSE 34 CONTROL SYSTEMS II

MODULE 34-1 Introduction to Transfer Functions

MODULE 34-2 Frequency Response Analysis

MODULE 34-3 Combination Control Systems

MODULE 34-4 Controller Tuning

MODULE 34-5 Operational Amplifiers

MODULE 34-6 Microprocessor Utilization

⇨ MODULE 34-7 Microprocessor Programming

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INTRODUCTION

A computer program is a step-by-step sequence of instructions entered into a computer. When the program is properly executed, the computer produces the solution to the problem submitted it. However, the validity of a computer's results depends upon accurate programming.

Programming technqiues for a microprocessor differ little from a larger computer. However, a microprocessor is associated with a limited number of machine instructions, fewer registers, and usually less complicated hardware interfaces. Therefore, the microprocessor programmer must (1) be more aware of individual bit assignments, (2) transfer data from register to intermediate (temporary) RAM locations and back to the registers later for use, and (3) set up special registers for special-purpose instructions. When using BASIC, the programmer avoids (2) and (3) because the interpreter generates the actual machine code for the programmer. BASIC, however, has liabilities of which the programmer must be aware. BASIC is very slow to execute and, consequently, cannot be used in time-critical situations.

The software functions taken up by microprocessors in the nuclear power plant can be summarized as follows:

- Analog and digital data processing, which includes pre-filtering, noise rejection, linearizing, monitoring of level changes, and monitoring of hardware status.
- Recording of past activities. In case of a serious malfunction, the causes may be determined immediately or at a later time.
- Complex calculations based upon changing input data; for example calculations of neutron flux from the interior of reactor cores.
- Computer control of the internal systems primary to the plant.

MODULE PREREQUISITES

The student should have completed Course 2, "Radiation Protection I"; Course 3, "Principles of Process Instrumentation"; Course 6, "Instrumentation and Control of Reactors and Plant Systems"; Course 33, "Control Systems I"; and all previous modules of this Course, especially Module 34-6, "Microprocessor Utilization."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
    - Operating system.
    - Polling.
    - Interrupt routine.
    - Line frequency check.
    - Main frame.
    - Microprocessor.
2. Explain how input/output (I/O) operations are performed on a typical microprocessor.
3. Discuss the two methods of I/O control and what the differences are.
4. Explain why ADC and DAC devices are needed.
5. Describe how the CPU knows when to transfer data to or from a device.
6. Give the reasons why programming standards for nuclear power plants are more rigorous than for other industrial applications and what some of these standards are.
7. Explain how flow charts can be misused when a program is designed only from flow charts.

8. Write or modify a simple program in BASIC to control meter deflection, given the necessary data.
9. Modify simple programs to make them easier to read.

INPUT/OUTPUT OPERATIONS

Before the microprocessor hardware functions summarized in the Introduction can be understood properly, the transportation of data into and out of the microprocessor must be studied.

Data is received into the computer through the use of I/O ports, which may be either latched or not, depending upon the microprocessor chosen. Each I/O port has a number assigned to it (typically a number from 0 to 255). Each port is associated with 8 bits, each of which is "on" or "off" (1 or 0). The programmer must be careful, however, when interfacing different devices to the computer since different hardware devices implement both positive and negative logic. The meaning of "on" (a set bit) to the microprocessor should be standardized for all devices. Most interface cards allow the logic to be flipped, if needed, for any bit.

In computer language, the term "read" describes data brought into the computer's memory from a device or devices. Likewise, the term "write" is applied to data sent out from the computer's memory to the device(s). However, data can be read or written before the device has finished a previous "read" or "write." In this case, the device is said to be "busy," and data cannot be transferred. To avoid the busy problem, the programmer may check a status bit for that device. Devices such as line printers or ADC (analog or digital) devices contain a status bit that indicates "ready" to the CPU. By reading the I/O port that contains the status bit, the programmer knows when the data is available. He periodically checks the status bit for a ready indication. When the ready bit goes on, the computer can read from, or write to, the device.

This method of I/O control is referred to as "status control." It has been implemented through many different schemes. The easiest, and one of the most common, ways that status control has been organized to service all of its I/O devices (termed "peripherals") is a round-robin scheme that operates as follows:

- The CPU (Central Processing Unit) asks device 1 if it has data to send or is ready to receive data. This is done by reading of the I/O port that contains the status bit.
- If the status bit is not set (not ready), then the CPU goes on to device 2. The same question is posed to device 2 by reading of the I/O port that contains the status bit.
- If device 2 is not ready, the the CPU tries the next device, and so on, until it eventually finds a device that is ready.

The CPU cycles through all devices in this manner. This method of status control is termed "polling." Other more sophisticated methods of status control have been used, but the basic principles remain the same.

There is a second method of I/O control that immediately tells the CPU that data is available or that the device is ready to accept data. In the case of status control, it has been shown that the device must wait its turn to notify the CPU that it is ready. This second method, called "interrupt control," utilizes a control line to stop the processor from executing the current instructions and to attend to the device. How does the CPU know which device? The usual hardware implementation involves transfer of a device number, termed "device address," to the CPU via a register. Each device address has a memory location associated (wired) with it. The CPU then stops its execution, saving the program counter in memory. The program counter contains the address of the next instruction in order that it may resume where it left off. The CPU then fetches the instruction found at the location associated with the device address and continues execution.

The instruction executed is a "jump instruction" (GOTO), which sends the CPU to the address in memory of the interrupt routine for its instructions. If this process seems confusing, it is not: The underlying principles are simple. Interrupts are merely requests for immediate attention put out from a device. The CPU suspends the job it is working on and executes the routine especially written to do the expected I/O transfer. This special program is called an "interrupt routine," and a separate one exists for each device. Other jobs besides I/O can be done by interrupt routines, as shall be discussed later on.

Data input to the computer cannot be processed unless it is in a digital format (ones and zeros). Analog data presented to the computer, therefore, is converted to digital data prior to being read by the computer. Analog data is defined as "any data that is continuous or nondiscrete by nature." A typical wall clock with two hands is an example of an analog device. Data of this nature is changed to discrete or digital format in order that it can be understood by the microprocessor. Therefore, any hardware device that uses current - an analog deflection meter, for example - is converted by the use of an analog-to-digital convertor (ADC). Likewise, data output to analog devices is converted by the use of DACs (digital-to-analog convertors).

OPERATING SYSTEMS

The microprocessor computer program in the nuclear power plant has many tasks to accomplish. Some of these tasks include control of flow through a line; opening and closing of valves; turning on of motors, pumps, and lights; sounding alarms; or processing of radiation counts from a radiation detector. If all of these tasks are of equal importance, then the program simply may cycle from one task to another, although this is most often not the case. Time is a crucial factor; for example, a warning horn should sound immediately, not a few seconds later, whenever high radiation is found in a personnel area. This task must assume more importance; thus, its priority is boosted ahead of other tasks.

Data that has been input from a device, must be used before additional data is written over it. 'From these examples one sees that computer processing activities are divided into two types; synchronous events and nonsynchronous events. Synchronous events are those events that occur at a fixed time: They repeat, or cycle. Asynchronous events occur on a nonrepetitive, as-needed basis.

In order to organize the various programming activities into something that performs all the processing in a timely, efficient manner, the microprocessor programmer constructs an operating system. The operating system is a program, usually written in assembly language, that —

- Schedules system tasks.
- Manages the frequency for synchronous tasks.
- Controls input/output operations.
- Controls interrupt processing.

The operating system establishes which tasks are most important and executes them on a priority basis. It may halt a task and suspend it when it is time for a task of higher importance to operate.

A piece of hardware is required to manage the frequency of synchronous tasks. Something as simple as a line frequency clock usually is precise enough. This clock employs ordinary 60-hertz power to generate interrupts once per cycle. The interrupt routine for this clock, therefore, keeps a count of the number of times it is called and can provide that count to start the synchronous tasks. For example, if a task must check radiation counts once every second, then whenever the counter in the line frequency clock interrupt routine reaches 60, it is time to start the task that reads the radiation counter values.

STRUCTURED DESIGN AND PROGRAMMING

The software required by the nuclear power industry – and, in fact all industry over recent years – has become increasingly expensive in relation to hardware costs. Software expenses have continued to rise, while the new miniaturization of digital hardware has brought hardware costs down. (Refer to Figure 34-7-1.)

An important solution to cutting software costs has been a more structured approach to software design. This approach to solving complex computer problems has been especially important to those programmers who must control nuclear processes and monitor personnel safety.

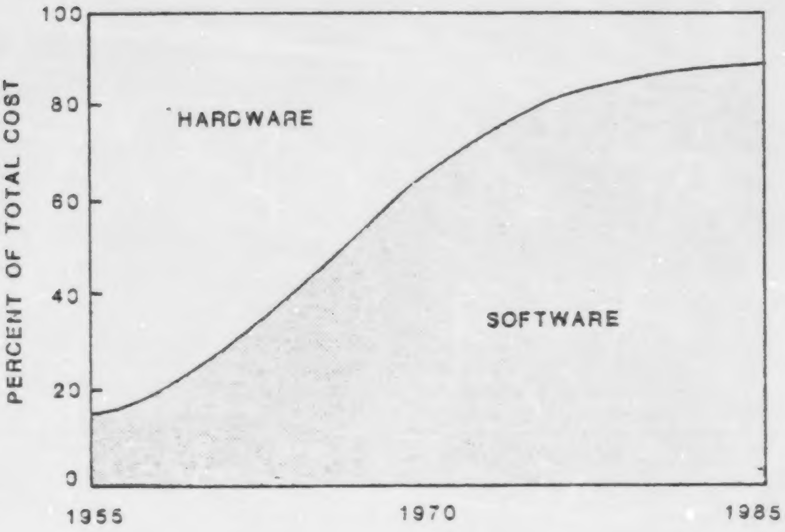


Figure 34-7-1. Increasing software costs as compared with decreasing hardware costs.

The use of structure techniques in programming has helped to make the computer program more easily understood and, therefore, less prone to error. The increased readability has made a dramatic difference in the ability of programmers to modify existing programs. Structured design is a building-block approach to writing of computer programs: It is a procedure for the construction of programs from a set of software modules that permits the definition of any algorithm.

The basic elements have one thing in common — one entry point and one exit point. Different tasks, therefore, can be combined with a minimum of interface problems. A very important part of structure programming, as one can see from the following example, is the reduction in program paths. The closer to a linear flow (similar to the way a book is read), the better the program.

Consider the following simple program that reads in a value to be processed, checks to determine if it is accurate, and then processes it. Upon receipt of a bad value or end number (255), the program stops.

```
05   INPUT A
10   GOTO 35
20   IF A = 255 GOTO 99
25   GOTO 70
35   IF A <20 GOTO 50
40   GOTO 20
50   PRINT 'INVALID VALUE RECEIVED'
60   GOTO 99
70   CALL PROCESS
80   GOTO 05
99   STOP
```

The same program written in nonstructured form to do exactly the same thing is as follows:

```
05   INPUT A
10   IF A = >20 AND A < >255 GOTO 70
20   REM '************'
25   REM 'TERMINATION SECTION'
30   REM '************'
40   IF A >20 THEN GOTO 99/ REM 'NORMAL TERMINATION'
50   PRINT 'INVALID VALUE RECEIVED'
55   GOTO 99
60   REM '************'
62   REM 'PROCESS THE DATA'
65   REM '************'
70   CALL PROCESS
75   GOTO 05/ REM 'GO BACK AND READ ANOTHER INPUT'
99   STOP
```

Which program is easier understood? Which program could be understood and modified more quickly with less chance for error? Both programs performed the job equally well, but the structure program enables the programmer to grasp the details more readily. It emphasizes readability and reduces unnecessary program paths. GOTOs that branch backward are strongly discouraged, as they destroy readability.

The advantages of structured design over other methods can be summarized as follows:

- Testing costs are lower. Up to 1/2 the time required to debug a program can be saved.
- Lower maintenance costs. Easier understandability has meant easier changes and fewer errors.
- Lower development costs. The project time to write a program has been shortened. This means lower salaries, supplies (such as line printer paper), and supervisory support.
- Reliability. An analogy would be in cars: Which car would tend to last longer – the one with highly complicated engine or the simple one with very few moving parts?
- Efficiency. The simpler program usually requires fewer instructions, less memory, and less machine execution time.

Which of the above have been, and continue to be, attractive to the nuclear power industry? Reliability stands high on the list. There has not been, and cannot be, a large margin for error in control and safety-oriented programs. In addition, the other four advantages have provided the industry with a partial solution to the problems of increasing support costs for nuclear power plants.

One of the important principles of structured programming is the use of mnemonic variable names. Consider the following three examples:

1. `X=V+460*Z AND`
2. `PROCESS$FLOW=DUCT$TEMPERATURE+460*DIFFERENTIAL PRESSURE`
3. `PFLOW=DTEMP+460*DPRESS`

Obviously, all the letters found in example 2 above cannot be used in BASIC; but in many high-level languages, a large number of letters can be employed. Example 3 is a compromise that enables the programmer to obtain an immediate knowledge of what the equation does. Most BASIC interpreters, unfortunately, permit only one or two letters.

The use of high-level programming languages has also been important. BASIC, FORTRAN, ALGOL, and PL/1 are examples of high-level languages. These languages have been termed "high level" because one statement generates many actual machine instructions.

Low-level langauge (assembly language) is quite different, in that the programmer must tell the machine each and every minute detail. As an example, to perform a simple addition, the low-level programmer must load register A with a value, load register B with another value, add the two registers, and then store the result into memory somewhere. This procedure requires four instructions, or statements, that easily can be accomplished in BASIC with the one statement: A = B + C.

The use of high-level languages has increased steadily throughout industry. With a fewer number of statements to do the same job, these languages provide a higher degree of reliability.

FLOW CHARTS

Another aspect of structured design involves the use of flow charts. Flow charts have been a traditional method of ensuring that computer logic is exact and without error. Misuse of this tool, however, can create problems, which if not remedied cause the program to "get out of control." The best procedure is to segment the program into logical groupings during the initial design stages and then to consider the use of the flow chart at a much more detailed level.

Flow charts are useful in tracing the logic of a program; however, when a program is written, there is a tendency to reuse logic. This fact, and the natural tendency to orient flow charts toward a sequence of actions rather than toward a group of functions, cause them to be dangerous on a broad scale.

CONTROL APPLICATIONS

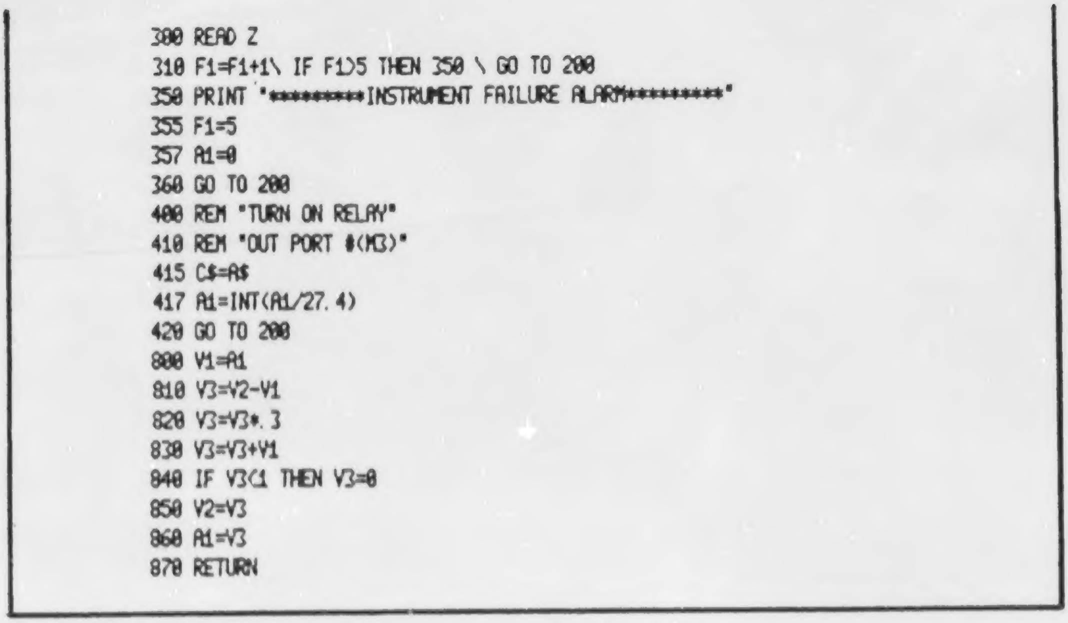
TYPICAL BASIC PROGRAM FOR THE CONTROL OF LIQUID LEVEL IN A STORAGE TANK

The computer program in Table 34-7-1 is written in BASIC and is an example of a typical program that would be used in the process control in a nuclear plant. The application is liquid level control in a storage tank. Table 34-7-2 gives the output from this program.

The program in Table 34-7-1 is explained in detail following Table 34-7-2.

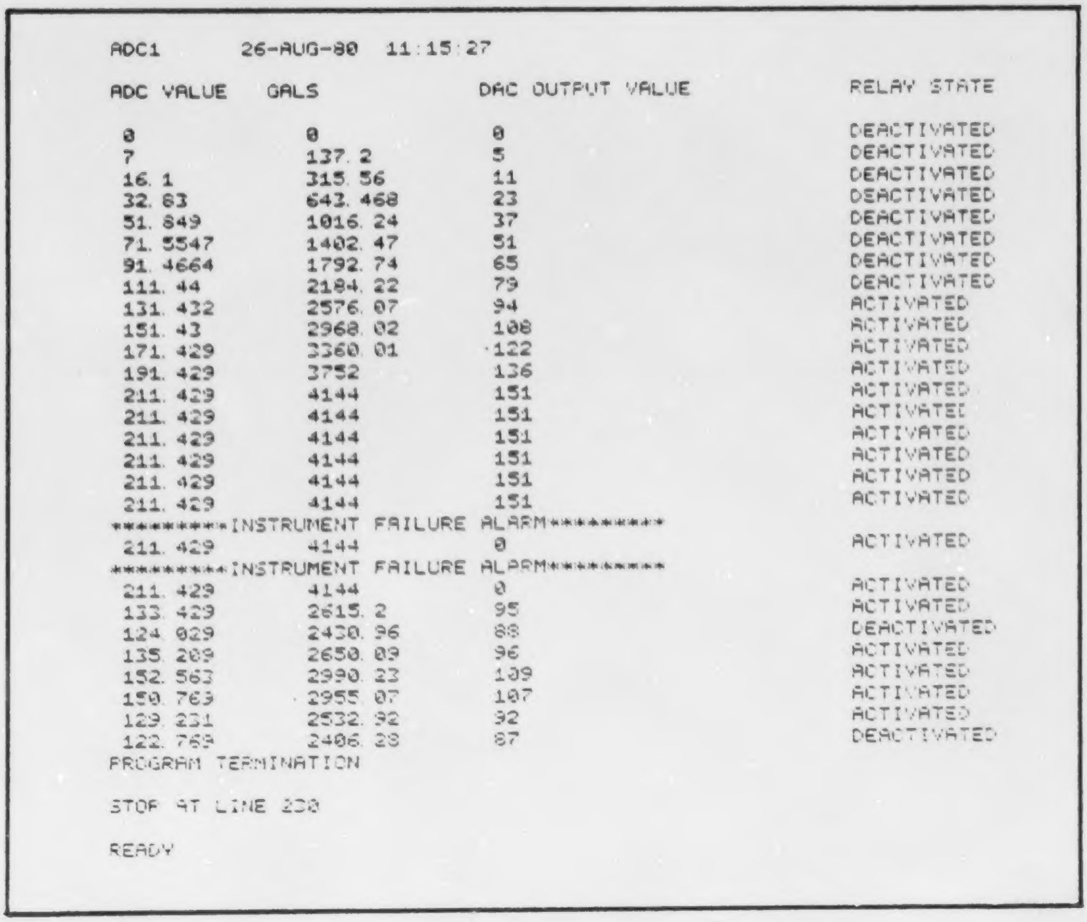
TABLE 34-7-1. MICROCOMPUTER PROGRAM WRITTEN IN BASIC LANGUAGE FOR LIQUID LEVEL CONTROL IN A STORAGE TANK.

```
1 RESTORE
2 A$="ACTIVATED"
3 B$="DEACTIVATED"
4 DIM C$(18)
5 PRINT "ADC VALUE   GALS","DAC OUTPUT VALUE","RELAY STATE"
6 PRINT
9 U1=255
10 L1=0
11 A2=2500
12 F1=0
13 DATA 1,1,1,10,1,20,1,40,1,60,1,80,1,100,1,120,1,140,1,160,1,180
14 DATA 1,200,1,220,240,255
15 DATA 0,10,0,10,0,10,0,10,0,10,0,10,1,100,1,120,1,140,1,160,1,150,1,120,1,120
18 FOR I=1 TO 27
20 REM "HAS THE ADC CONVERTED THE ANALOG INPUT?"
22 REM "(C1=IN(PORT#))"
30 READ C1
40 IF C1<>1 THEN 300
50 REM "READ ADC VALUE"
60 REM "A1=IN(PORT #)"
70 READ A1
75 REM "SMOOTH ADC DATA"
80 GOSUB 800
90 REM "MULTIPLY BY CONVERSION FACTOR FOR PROPER UNITS"
95 REM "0 - 255  INPUT = 0 - 5000 GALLONS VOLUME IN TANK"
110 IF A1>U1 THEN 310 \ REM " IS ADC ABOVE UPPER INSTRUMENT LIMIT?"
120 IF A1<L1 THEN 310 \ REM " IS ADC BELOW LOWER INSTRUMENT LIMIT?"
122 F1=F1-1 \ IF F1=-1 THEN F1=0
123 S1=A1
125 A1=A1*19.6
127 G1=A1
130 IF A1>A2 THEN 400 \ REM "INST LIMITS OK - ABOVE ALARM LIMIT?"
140 REM "ADC IS WITH IN NORMAL RANGE - MAKE SURE VALUE IS CLOSED"
150 REM "OUT PORT#(M2)"       \ REM "TURN OFF VALVE"
160 REM "SCALE OUTPUT FOR DAC (0 - 255 = 0 - 7000 GALLONS)"
162 C$=B$
170 A1=INT(A1/27.4) \ REM "CONVERSION FACTOR = 7000/255"
180 REM "OUTPUT TO DAC"
190 REM "OUTPUT PORT#(A1)"
200 PRINT S1,G1,A1,,C$
207 REM "SIMULATE METER"
210 NEXT I
220 PRINT "PROGRAM TERMINATION"
230 STOP
```



```
300 READ Z
310 F1=F1+1\ IF F1>5 THEN 350 \ GO TO 200
350 PRINT "**********INSTRUMENT FAILURE ALARM**********"
355 F1=5
357 A1=0
360 GO TO 200
400 REM "TURN ON RELAY"
410 REM "OUT PORT #(M3)"
415 C$=A$
417 A1=INT(A1/27.4)
420 GO TO 200
800 V1=A1
810 V3=V2-V1
820 V3=V3*.3
830 V3=V3+V1
840 IF V3<1 THEN V3=0
850 V2=V3
860 A1=V3
870 RETURN
```

TABLE 34-7-2. OUTPUT FROM PROGRAM IN TABLE 34-7-1.



```
ADC1       26-AUG-80  11:15:27

ADC VALUE   GALS            DAC OUTPUT VALUE            RELAY STATE

 0              0           0                           DEACTIVATED
 7              137. 2      5                           DEACTIVATED
 16. 1          315. 56     11                          DEACTIVATED
 32. 83         643. 468    23                          DEACTIVATED
 51. 849        1016. 24    37                          DEACTIVATED
 71. 5547       1402. 47    51                          DEACTIVATED
 91. 4664       1792. 74    65                          DEACTIVATED
 111. 44        2184. 22    79                          DEACTIVATED
 131. 432       2576. 07    94                          ACTIVATED
 151. 43        2968. 02    108                         ACTIVATED
 171. 429       3360. 01    122                         ACTIVATED
 191. 429       3752        136                         ACTIVATED
 211. 429       4144        151                         ACTIVATED
 211. 429       4144        151                         ACTIVATED
 211. 429       4144        151                         ACTIVATED
 211. 429       4144        151                         ACTIVATED
 211. 429       4144        151                         ACTIVATED
 211. 429       4144        151                         ACTIVATED
*********INSTRUMENT FAILURE ALARM**********
 211. 429       4144        0                           ACTIVATED
*********INSTRUMENT FAILURE ALARM**********
 211. 429       4144        0                           ACTIVATED
 133. 429       2615. 2     95                          ACTIVATED
 124. 029       2430. 96    88                          DEACTIVATED
 135. 209       2650. 09    96                          ACTIVATED
 152. 563       2990. 23    109                         ACTIVATED
 150. 763       2955. 07    107                         ACTIVATED
 129. 231       2532. 92    92                          ACTIVATED
 122. 769       2406. 28    87                          DEACTIVATED
PROGRAM TERMINATION

STOP AT LINE 230

READY
```

The Required Hardware for Program in Table 34-7-1

The program in Table 34-7-1 is written in standard DEC-11 BASIC. It does not allow direct input and output to peripheral devices as do some extended BASICs; therefore, it is written to simulate data input and output. Remark statements have been included to show the student where to insert in and out statements if the student has an extended version of BASIC that allows this procedure. The following hardware is required for the procedure:

- Liquid Level Transducer: Output would be an analog signal representing liquid level in the storage tank.
- A-To-D Converter (ADC): Converts the analog liquid level to digital form.
- 8885 Microprocessor: Runs the BASIC program and handles routine input/output to controlling devices.
- D-To-A Converter (DAC): Outputs an analog signal to record device representing liquid level.
- 8-bit Parallel Port: By setting one of the bits in this parallel port, a relay is actuated to control liquid level in the tank.

Data Initialization Statements of Program in Table 34-7-1

Statements 2-6 restore the data pointer and set up and print the header for the printed output:

```
1 RESTORE
2 A$="ACTIVATED"
3 B$="DEACTIVATED"
4 DIM C$(18)
5 PRINT "ADC VALUE   GALS","DAC OUTPUT VALUE","RELAY STATE"
6 PRINT
```

Statements 9-15 initialize the variables –

U1=upper instrument limit and
L1=lower instrument limit.

These instrument limits provide an upper and lower range of values from the ADC. If either of the limits is exceeded, an alarm is provided to notify the operator of a possible hardware failure.

The F1=instrument failure counter allows five consecutive instrument failures before it alarms the operator. A2=level control point in gallons and is the control level at which point the relay to empty the tank is actuated.

Lines 13-15 are simulated ADC input data statements. They can be changed to meet the individual data input requirements. The sequence of the data input is as follows:

- The first number is the "convert complete" flag. If this number is not one, the program handles it as if the data following is invalid.
- The second number is any value from 8 to 255 that simulates the input from the 8-bit ADC. This sequence is repeated for any number of input values.
- Examples of first and second numbers are

  1,24,1,233,...8,255,0,233,1.223,1,233.

```
9 U1=255
10 L1=0
11 A2=2500
12 F1=0
13 DATA 1, 1, 1, 10, 1, 20, 1, 40, 1, 60, 1, 80, 1, 100, 1, 120, 1, 140, 1, 160, 1, 180
14 DATA 1, 200, 1, 220, 240, 255
15 DATA 0, 10, 0, 10, 0, 10, 0, 10, 0, 10, 0, 10, 1, 100, 1, 120, 1, 140, 1, 160, 1, 150, 1, 120, 1, 120
```

At this point, the ADC status should be checked to ensure that it has converted the analog input signal and that there is no hardware problem with the ADC. Also, a loop is set up to run X number of simulated inputs.

Lines 22 and 60 show where some BASIC interpreters allow the use of "in" statements, directly reading an 8-bit value from an I/O port. If the student's BASIC allows this, these statements should be used rather than the read/data statements.

```
18 FOR I=1 TO 27
20 REM "HAS THE ADC CONVERTED THE ANALOG INPUT?"
22 REM "(C1=IN(PORT#))"
30 READ C1
40 IF C1<>1 THEN 300
50 REM "READ ADC VALUE"
60 REM "A1=IN(PORT #)"
70 READ A1
```

After the data is read (or input directly), it is smoothed by the smoothing routine at line 800.

```
75 REM "SMOOTH ADC DATA"
80 GOSUB 800
90 REM "MULTIPLY BY CONVERSION FACTOR FOR PROPER UNITS"
95 REM "0 - 255  INPUT = 0 - 5000 GALLONS VOLUME IN TANK"
```

The value read in is checked against the present instrument limits; and if it is in the proper range, it is multiplied by a conversion factor to produce a value unit in gallons. F1 is decremented to indicate that the value was in proper range. If the value is outside the instrument limits, control is passed to line 310 to handle instrument failures.

```
110 IF A1>U1 THEN 310 \ REM " IS ADC ABOVE UPPER INSTRUMENT LIMIT?"
120 IF A1<L1 THEN 310 \ REM " IS ADC BELOW LOWER INSTRUMENT LIMIT?"
122 F1=F1-1 \ IF F1=-1 THEN F1=0
123 S1=A1
125 A1=A1*19.6
127 G1=A1
```

Line 130 determines if the calculated value (A1) has exceeded the present control point for actuating the tank drain relay. If A1 is less than the setpoint (A2), the relay is de-energized. If A1 is greater, the relay is energized. Line 150 is the point at which the valve control is effected directly with the "out" statement, allowed with some BASICs. In this example, only a printed message indicates the relay state.

Lines 170 through 200 simulate the DAC output value that normally would go to an analog meter. The value is scaled to correspond to the range of the student's meter and output by printing the results out the student's terminal. However, if the student has a DAC and is running the proper BASIC interpreter, the "out" statement may be used as indicated at line 190.

```
130 IF A1>A2 THEN 400 \ REM "INST LIMITS OK - ABOVE ALARM LIMIT?"
140 REM "ADC IS WITH IN NORMAL RANGE - MAKE SURE VALUE IS CLOSED"
150 REM "OUT PORT#(M2)"        \ REM "TURN OFF VALVE"
160 REM "SCALE OUTPUT FOR DAC (0 - 255 = 0 - 7000 GALLONS)"
162 C$=B$
170 A1=INT(A1/27.4) \ REM "CONVERSION FACTOR = 7000/255"
180 REM "OUTPUT TO DAC"
190 REM "OUTPUT PORT#(A1)"
200 PRINT S1,G1,A1,,C$
207 REM "SIMULATE METER"
210 NEXT I
220 PRINT "PROGRAM TERMINATION"
230 STOP
```

This is the instrument limit failure subroutine. If the ADC has not converted the input analog signal or if the value input exceeds the specified range, a counter is incremented by one. If this count exceeds five successive failures, an alarm message is printed; and the output value is set to 0 (zero).

The read Z statement in line 300 is used to keep the read pointer in proper alignment with the data.

```
300 READ Z
310 F1=F1+1\ IF F1>5 THEN 350 \ GO TO 200
350 PRINT "**********INSTRUMENT FAILURE ALARM**********"
355 F1=5
357 A1=0
360 GO TO 200
```

This subroutine sets up the proper message to be printed when the relay is energized. Line 410 indicates where the programmer inserts the "out" statement when running this program with the DAC hardware, actuating the control relay.

```
400 REM "TURN ON RELAY"
410 REM "OUT PORT #(M3)"
415 C$=A$
417 A1=INT(A1/27.4)
420 GO TO 200
```

This is the input ADC value smoothing algorithm:

```
800 V1=A1
810 V3=V2-V1
820 V3=V3*.3
830 V3=V3+V1
840 IF V3<1 THEN V3=0
850 V2=V3
860 A1=V3
370 RETURN
```

THE MICROPROCESSOR ANALYZER

The microprocessor analyzer, also referred to as the "logic analyzer," is a valuable software debugging aid. Each analyzer, being equipment specific, is utilized with a particular type or model of microprocessor. The purpose of the analyzer is to avoid the decoding of binary bit patterns. Instruction bit patterns are decoded automatically back into nmemonic operation codes for programmer convenience. The analyzer can monitor many external control signals in order that the results of program execution and the software environment can be displayed during debugging.

EXERCISES

1. Suppose an operating system used a 60-hertz clock. If a software counter increments the count each time an interrupt from the clock is received, how many counts will be necessary to activate a task that should execute every 1.5 seconds?
2. If an operating system is equipped with a 1-kilohertz clock instead of a 60-hertz clock, what is the smallest increment of time that can be discerned?
3. If a 1-kilohertz clock is utilized, how many bits are required in the software counter to enable activation of a task at 1.0-second intervals?

MATERIALS

Microprocessor with a BASIC Interpreter and with facilities for keyboard entry. (A microprocessor is required only if Procedure 2 is performed.)
Pencils.
Paper.

PROCEDURES

PROCEDURE 1: MODIFICATION OF A MICROPROCESSOR PROGRAM.

This pencil-and-paper procedure involves the modification of the process-control program in Table 34-7-1.

1. Refer to Table 34-7-1, which is to be modified in accordance with the instructions in Steps 2-7.
2. Read ADC input as pressure (0 to 2000 psi).
3. ADC readings should not go below 10 or above 200.
4. Control a relay that is actuated when the pressure drops below 300 psi and is deactivated above 1700 psi.
5. Alert operator with alarms when the pressure falls below 250 psi and rises above 1800 psi.
6. Scale pressure output to meter with range of 0 to 2500 psi.
7. Change print-out header to reflect proper units and alarm conditions.

PROCEDURE 2: ENTRANCE AND EXECUTION OF A PROGRAM WITH A MICROPROCESSOR.

1. Refer to the program print-out results obtained in Procedure 1.
2. Enter and execute the modified program (modified from the program in Table 34-7-1) obtained in Procedure 1.
3. Discuss the output provided by the microprocessor.

DATA TABLE

None.

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TEST

1. Define the following terms:

   a. Operating system.

   b. Polling.

   c. Interrupt routine.

   d. Line frequency clock.

   e. Main frame.

   f. Microprocessor.

2. How are input/output operations performed on a typical microprocessor?

3. List and explain the two methods of I/O control and how they are different.

4. Why are ADC and DAC devices needed?

5. How does the CPU know when to transfer data to or from a device?

6. Why are programming standards for nuclear power plants more rigorous than for other industrial applications? Explain some of the standards.

7. How can flow charts be misused when a program is designed from them alone.

8. Structure the following program to eliminate as many unnecessary program paths as possible. Use REM statements to "block" the sections. (Note that although most BASIC interpreters allow only one or two letters, more were used in this program for clarity.)

```
 05  COUNT = 0
 10  TOTAL = 0
 15  INPUT NMBR
 20  IF NMBR <0 GOTO 65
 30  TOTAL = TOTAL + NMBR
 40  COUNT = COUNT + 1
 50  GOTO 75
 65  PRINT 'INVALID ENTRY - REENTER'
 70  GOTO 15
 75  IF COUNT = 10 GOTO 99
 80  GOTO 15
 99  AVRGE = TOTAL/COUNT
100  PRINT 'THE AVERAGE IS', AVRGE
```

9. Using input or data statements, write a program to read a port from the data below. These inputs represent radiation counts supplied from a Geiger-counter device. The program should reject data less than zero and should print the average number and the mean number of radiation counts. The data should be printed as it is read in.

DATA: 5,7,3,-3,3,5,10,15,22,12,7,0.

NUCLEAR TECHNOLOGY

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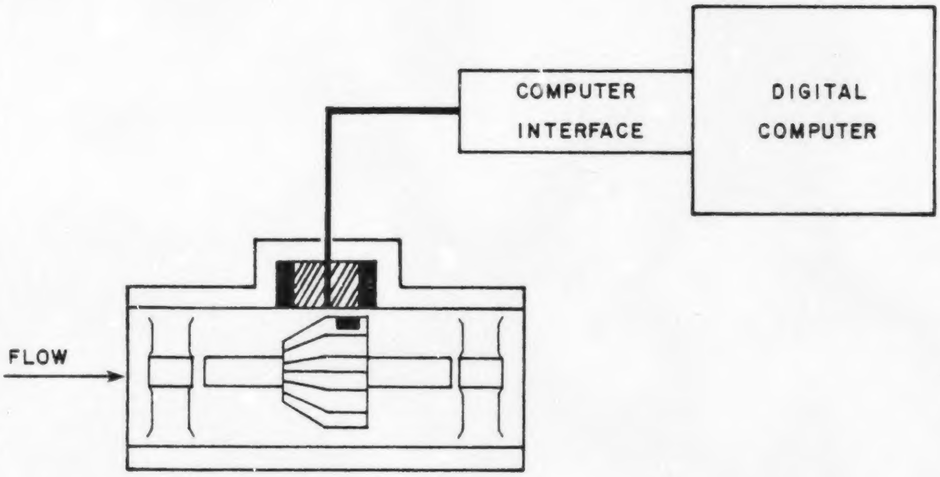
COMPUTER INTERFACE
DIGITAL COMPUTER
FLOW

CONTROL SYSTEMS II
COURSE 34

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

NUCLEAR TECHNOLOGY SERIES
INDEX
for
COURSE 34, CONTROL SYSTEMS II (SEVEN MODULES)

NOTE: Each module in this Course is numbered separately, and the page numbers begin with page 1 in each module. Therefore, this Index lists for each entry the module number (underlined), followed by a comma and the page number. Figures and tables are listed by their numbers, followed by the module and page number in parentheses. A Master Index is available in a separate volume. This general index merges all index entries from the 35 Nuclear Courses. It is a valuable research tool, with which the student or researcher can locate all the references to any subject within the 35 Courses.

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